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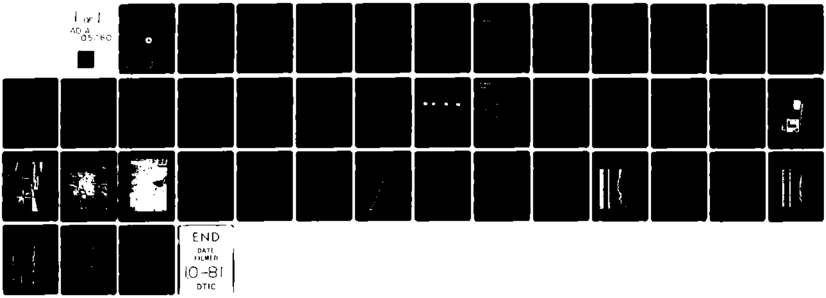

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FLIGHT EVALUATION OF LORAN-C AS A HELICOPTER NAVIGATION AID IN THE BALTIMORE CANYON OIL EXPLORATION AREA

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16. Abstract

A series of flight tests were conducted from March through May 1979 to investigate the use of long range navigation (LORAN)-C as a helicopter navigation system in the offshore New Jersey Baltimore Canyon oil exploration area. Tests were flown aboard the Federal Aviation Adminstration (FAA) Technical Center's CH-53A using a Teledyne Systems TDL-711 LORAN Micro-Navigator. The purpose of the tests was to determine the accuracy and operational usability of LORAN-C for offshore en route navigation and nonprecision approaches. The total system accuracy met or exceeded the requirements of Advisory Circular (AC) 90-45A "Accuracy Requirements of Area Navigation Systems" for terminal and en route phases of flight, provided the proper LORAN triads were selected. The LORAN-C System did not meet AC 90-45A nonprecision approach accuracy criteria.

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INTRODUCTION

BACKGROUND.

The Federal Aviation Administration's (FAA's) "Helicopter Operations Development Plan" of September 1978 (Report FAA-RD-78-101) recognizes the special problems of rotary wing aircraft and addresses the inadequacy of present line-of-sight navigation systems. It also calls for the evaluation for helicopter use of present long-range, over-the-horizon navigation systems as a near term objective. To accomplish this, several test programs were conceived. The program covered here is the evaluation of long range navigation (LORAN)-C as a low-level helicopter navigation system in the offshore and coastal New Jersey areas. A Product Plan outlining technical objectives and test procedures was written in October 1978. Design and construction of a data collection system was begun at the same time. Installation in the CH-53A test aircraft followed, with system checkout and shakedown flights in February 1979. Data collection flights were conducted during the period from March through May 1979. The 27 test flights comprised a total of 41 hours of flying time, 35 departures, 42 en route segments, 35 approaches, and 6 "box" patterns.

LORAN-C FUNDAMENTALS.

LORAN-C is a passive, pulsed, low-frequency hyperbolic navigation system. A master station and several secondary stations, 200 to 1,000 miles apart, comprise a chain. The master station transmits a pulse train at 100 kilohertz (kHz) with a fixed repetition rate, the period of which is called the group repetition interval (GRI). Each secondary station transmits a similar pulse train, also at 100 kHz, synchronized to the master station but delayed a fixed interval, the coding delay. A typical pulse train is shown as figure 1. For a given location, the time between reception of the master pulse train and a secondary train depends on three things: distance to the master, distance to the secondary, and time delay between master and secondary. The LORAN-C receiver can, thus, measure the difference in time/distance from its location to the master and secondary station. A line of constant time/distance difference is called a line of position (LOP). It is a hyperbola with the two stations as its foci. By measuring two time differences, between the master and two of it's secondaries, the receiver can compute it's location at the intersection of two hyperbolae. The Northeast U.S. Chain was used for these flight tests. A map and table of parameters for this chain is included as figure 2 and table 1.

The major factors which affect the accuracy of LORAN-C navigation systems are: (1) signal strength, (2) signal-to-noise ratio, (3) diurnal variation, (4) station geometry, and (5) propagation anomalies. These factors are discussed below.

1. Signal strength is primarily a function of the distance to the station and propagation conditions between the station and the receiver.

2. Signal-to-noise ratio can be degraded by several factors: a high power transmitter in the very low frequency (VLF) band near 100 kHz can overload a receiver's input circuits; precipitation static can be generated by the small static charges on raindrops or moisture droplets as the aircraft flies through precipitation. Neither effect was studied during these tests.

3. Solar radiation causes the upper layers of the atmosphere to ionize, producing the ionosphere, a shell of charged particles 150 to 250 miles above the earth. The ionosphere can reflect LORAN signals back to earth, arriving

TABLE 1. NORTHEAST U.S. CHAIN PARAMETERS

LORAN-C

NORTHEAST U.S. CHAIN
GRI 9960

REGIONAL MANAGER COMMANDER, ATLANTIC AREA
CHAIN MANAGER COMMANDER, ATLANTIC AREA
COORDINATOR OF CHAIN OPERATIONS LOCATION LORSTA SENECA, NY

STATION	FUNCTION	COORDINATES	EMISSION DELAY	INSTALLED EQUIPMENT	TRANSMIT ANTENNA	RADIATED POWER	REMARKS
SENECA NY	MASTER	42 42 50 603N 76 49 33 862W		SSX Solid state (56 HCG's)	700 foot monopole	800KW	Control for W [illegible] and Z Double rated to Great Lakes Chain
CARIBOU ME	WHISKY	46 48 27 199N 67 55 37 713W	13797 20usec	AN FPN 42	SLT	350KW	
NANTUCKET MA	XRAY	41 15 11 930N 69 58 39 090W	26969 93usec	AN FPN 42	625 foot monopole	275KW	
CAROLINA BEACH NC	YANKEE	34 03 46 040N 77 54 46 760W	42221 65usec	AN FPN 42	TLP	550KW	Double rated to SEUS Chain
DANA IN	ZULU	39 51 07 540N 87 29 12 140W	57162 06usec	AN FPN 44	625 foot monopole	400KW	Double rated to Great Lakes Chain
LORMONSITE CAPE ELIZABETH ME	MONITOR	43 33 54 817N 70 11 58 537W		AUSTRON 5000			Unmanned receiver site
LORMONSITE SANDY HOOK, NJ	MONITOR	40 28 17 035N 74 01 03 713W		AUSTRON 5000			Unmanned receiver site
LORMONSITE PLUMBROOK, OH	MONITOR	41 22 46 956N 82 39 38 530W		AUSTRON 5000			Unmanned receiver site
LORMONSITE MAYPORT FL	MONITOR	30 22 58 850N 81 25 13 105W		AUSTRON 5000			Unmanned receiver site

later than signals which have followed the curve of the earth's surface. These sky waves, if strong enough, can contaminate the LORAN ground wave and cause inaccuracies. The ionosphere is as much as 100 miles lower during daylight hours, thus, changing both the strength and delay of the sky wave contamination. Several flights were flown during dusk to investigate these diurnal effects.

4. Station geometry can have a significant effect on LORAN-C position measurement accuracy. A LORAN system is basically a time measurement system. The relationship between time measurement errors and position errors depends upon the receiver position with respect to the master and secondary stations and the position of the master and secondary stations with respect to each other. A LORAN receiver computes its position as being at the intersection of two LOP's; measurement inaccuracies actually widen this point into an area of uncertainty. In figure 3 it can be seen that for the same time measurement error, the position measurement error is greater using secondaries at Dana and Carolina Beach. This is caused by the LOP pairs crossing at a shallow angle and producing an elongated area of uncertainty. The position determination is more accurate between the secondary stations than in the region on either side of the stations. It is at its worst in the areas behind the stations, near what is known as the baseline extensions.

5. The propagation velocity of LORAN-C signals depends on the conductivity of the earth's surface over which the signals travel. Propagation velocity over seawater is constant and predictable. Propagation over land, however, varies according to the type of soil and terrain between the transmitter and receiver. These actual propagation velocty differences introduce an error into the time-difference to distance-difference conversion in a LORAN receiver's position computations. These propagation anomalies are responsible for a significant portion of LORAN system errors. A LORAN system with an accurate map or table of <u>actual</u> propagation velocities could be expected to produce more accurate position information.

SYSTEM DESCRIPTION

AIRBORNE EQUIPMENT.

The receiver used in these tests is a TDL-711 Micro-Navigator, manufactured by Teledyne Systems Corporation, Northridge, California, and distributed by Offshore Navigation, Incoporated, New Orleans, Louisianna. The system consists of an antenna with built in preamplifier, a receiver computer unit (RCU), and a control and display unit (CDU). In the Center's CH-53A installation, the antenna was installed on the top of the fuselage, just forward of the tail boom; the RCU was installed along with other project equipment in the aft cabin; and the CDU was mounted in the cockpit center pedestal, accessible to both pilot and copilot. The equipment and installation are shown in figures 4, 5, 6, and 7.

The TDL-711 computes and displays present position as both latitude-longitude (lat-long) and LORAN time differences (TD's). It will store up to nine waypoints as lat-longs or TD's; compute distance, bearing, and time en route to the selected "TO" waypoint; ground speed and ground track; desired track between the two active waypoints; and deviation from this track in nautical miles and degrees. Displayed bearings are magnetic and the pilot must enter local variation. The system will also navigate along an offset track, parallel to that defined by the waypoints. The TDL-711 generates TO-FROM and crosstrack deviation signals. These were displayed on the pilot's horizontal situation indicator (HSI) in this

installation. The basic TDL-711 stores the parameters for any two LORAN chains; either may be selected by the pilot. This installation included an option to select and use 16 triads. These may be in different chains, or different triads within the same chain. This was used after April 1979. The TDL-711 is also capable of "area calibration." In this mode the pilot enters a present position before flight, the receiver compares predicted TD's with actual measured TD's, and computes a correction factor to compensate for local propagation anomalies. It was not known for what extent of area or length of time a correction would be valid, so this area calibration was not used.

The TDL-711 "tracks" (measures and stores) time differences and signal-to-noise ratios of the master and three secondary stations. However, only the two selected secondaries are normally used. If one secondary becomes unusable, the backup is automatically selected by the receiver. If the master becomes unavailable, the LORAN receiver will operate in the "master independence" mode, using time differences between three secondary signals. These modes are not as accurate and the pilot is warned by flashing decimal points on the digital displays on the face of the CDU that navigation accuracy may be degraded.

AIRBORNE DATA COLLECTION SYSTEM.

The CH-53A airborne data collection system is based on a PDP 11/34M hostile environment minicomputer and a Litton LTN-51 inertial navigation system (INS). The minicomputer is equipped with dual floppy disc drives for program and data storage. An aircraft systems coupler was built by project personnel to interface aircraft parameters and LORAN receiver information to the minicomputer's internal data bus. A complete list of recorded parameters is included as appendix 1. All data were sampled and recorded at a 1-hertz (Hz) rate. The recorded parameters of interest to this effort are:

LORAN latitude and longitude

INS latitude and longitude

LORAN time differences

LORAN station track status and signal-to-noise ratios

LORAN HSI crosstrack deviation and navigation flag

Time of day, synchronized with ground tracking facilities.

TRACKING SYSTEM.

Most of the data in this report are based on using the Center's Extended Area Instrumentation Radar (EAIR) as the position reference. This is a C-Band transponder tracking radar located at the FAA Technical Center. This system records aircraft position in azimuth, elevation, range from the radar site, and time of each sample at a 10-Hz rate. The radar could track the helicopter through all phases of flight except below the horizon; e.g., on an approach to an offshore oil rig. During this phase of flight, the onboard inertial navigation system provided position reference. The EAIR radar at the maximum range flown during these tests has an accuracy of about 100 feet. The INS system has an accuracy of about 1,220 feet for the period of time it is used.

TEST PROCEDURES

TYPICAL TEST FLIGHT.

Several flight patterns were developed which simulated typical offshore oil rig logistic operations. These included standard instrument departures (SID), en route segments, and point-in-space

approaches (PISA). In conducting a standard instrument departure (figure 8) the helicopter would lift-off and proceed to the first departure waypoint, either under its own navigation or following vectors from air traffic control. At the first waypoint the aircraft would begin LORAN-C navigation, if not already using it, and continue climbing to en route altitude. (There was no specific vertical profile to be followed on the departure.) En route segments were flown under LORAN guidance, with a cruising altitude of 5,000 feet outbound and inbound.

Approaches to the oil platforms generally consisted of two lateral segments and vertical checkpoints, based on distances to waypoints. The approach to the Pacesetter III rig (figures 9 and 10 and table 2) is a typical approach. The pilot began the descent from en route altitude at waypoint Gas 50, approximately 30 miles from the platform. The first altitude check point is 1,000 feet, 5 miles from the Gas 70 waypoint. At Gas 70, the pilot descended to 400 feet, leveling at that altitude at least 4 miles from the platform. The pilot remained on LORAN-C guidance and may still have been on instrument flight rules; that is, no visibility. At 1/2 mile LORAN indicated distance to the platform the pilot proceeded to a visual landing if the platform was in sight, if not, he would have executed a missed approach. The Center's aircraft always executed missed approach procedures.

TABLE 2. PACESETTER IV PATTERN WAYPOINTS

LORAN-C
FLIGHT PATTERN NO. 5

WP NO.	NAME	TO OBS/DIST	LAT/LONG	ACY VOR/DME
1	CLOVE	Direct	39 24.6'/74 32.8'	162.5°/3.1
2	EAGLE	105°/8.0	39 23.9'/74 22.4'	120°/10.0
3	GAS 70	120°/60	39 02.9'/73 09.9'	120°/70
4	PACE-SETTER III	142°/7.3	38 58.1'/73 02.9'	122.4°/76.8
5	DELTA HOLD	238°/8.0	38 52.6'/73 10.4'	128°/74
6	GAS 50	324.6°/25.3	39 10.0'/73 34.0'	120°/10.0
7	EAGLE	300°/40	39 23.9'/74 22.4'	120°/10.0
8	FAWP	312°/3.6	39 25.9'/74 26.3'	113.2°/6.6
9	NORTH MAWP	312°/5.0	39 28.5'/74 31.8'	71.6°/2.4
10	VFR To FAA Technical Center			

The point-in-space approach to a land-based heliport is similar. It is based on conducting an approach to an easily recognizable geographic feature in the vicinity of the heliport, the missed approach waypoint, and proceeding under visual flight rules to the landing pad. In these tests two locations were chosen, both interchanges on the Garden State Parkway which pass close to the FAA Technical Center.

A typical land based point-in-space approach is shown in figure 8. The vertical check points are 2,000 feet at the final approach waypoint (FAWP), approximately 5 miles from the missed-approach point and 400 feet above ground level at the missed approach waypoint (MAWP). The Center aircraft proceeded visually from the MAWP to touchdown. The ground track of a flight to the Pacesetter III oil platform is shown in figure 11. The vertical profile of this approach is shown in figure 12.

The "box" pattern was used to test differing station geometries using several different pairs of secondaries. The pattern began and ended at the Center and included 20-mile legs along eight major points of the compass to determine error values as a function of direction of flight (see figure 13).

DATA ANALYSIS CRITERIA.

The data were analyzed to determine if they met the criteria of Advisory Circular (AC) 90-45A dated February 21, 1975. This document sets forth the accuracy requirements for area navigation systems used off-airways for en route, terminal, and nonprecision approach guidance. The necessary total system accuracies for non-very high frequency omnidirectional radio range (VOR) distance measuring equipment (DME) based area navigation (RNAV) systems are summarized here:

	Along-Track	Crosstrack
En Route (nmi)	1.5	2.5
Terminal (nmi)	1.1	1.5
Nonprecision Approach (nmi)	0.3	0.6

For this report, departures were considered to be the only terminal segments; that is, there were no terminal segments between en route and approach operations.

RNAV system errors come from two sources: airborne equipment errors and flight technical errors(FTE's). Airborne equipment errors are those associated with the reception and processing of the LORAN transmitted signals, the measurement of signal time differences, determination of position from time differences, and calculation and display of navigation parameters such as crosstrack deviation and steering commands. FTE's are caused by a pilot not closely following commands due to aircraft dynamics or work-load and distraction factors.

For a two-dimensional navigation system, along-track FTE is always considered to be zero. Total system crosstrack error (TSCT) is the sum of crosstrack airborne equipment error and flight technical error. Total system along-track (TSAT) error in a two-dimensional system is equal to along-track airborne equipment error.

AC 90-45A specifies particular values of FTE which must be added to airborne equipment error to determine total system crosstrack error. The root sum square subtraction of FTE from TSCT yields required airborne equipment crosstrack accuracy. Specified FTE and airborne equipment accuracies are as follows:

	En Route (nmi)	Terminal (nmi)	Nonprecision Approach (nmi)
FTE	2.0	1.0	0.5
Airborne Equipment Crosstrack Accuracy	1.5	1.1	0.3

DATA REDUCTION.

The EAIR tracking data was processed postmission in the FAA Technical Center's Honeywell 66/60 computer facility to produce tapes containing aircraft latitude, longitude, altitude, and time of day. These tapes were processed by project personnel to remove outliers (data points obviously in error caused by glitches in the recording system) and then time-merged with airborne data. In the merge process each sample of airborne data is combined with the closest (in time) sample of EAIR data. If no EAIR data were available within 0.25 seconds, the sample was deleted. INS position was compared with the EAIR position for times just before EAIR lost track of the aircraft below the horizon and just after it regained track as the aircraft regained altitude. A bias error and drift rate were computed from these positions and used to correct the INS position during this time. This corrected INS was used as position reference for the time EAIR was unable to track. LORAN position errors, in nautical miles (nmi) north and east, were determined from comparison of LORAN lat-long with EAIR or INS lat-longs. Errors greater than 20 miles in either direction were considered outliers and were deleted. North and east errors were resolved into components parallel and perpendicular to the desired track, as defined by the active waypoints, to produce along-track and crosstrack errors. These errors were then summed on a leg by leg basis to determine mean error, standard deviation, and coefficients of skewness and kurtosis. North, east, along-track, and crosstrack errors were plotted on a common time axis.

The TDL-711 outputs signal-to-noise ratios for master and each secondary as well as in-or-out track status. These were recorded in flight and plotted postmission on a time axis. These data were analyzed only qualitatively, no statistics were computed. The LORAN receiver does not output signal-to-noise ratios above +5 decibels (dB) so the plots are limited at this point.

Six measurements were calculated for each of four position error parameters for each segment flown. These are the mean, standard deviation, coefficients of skewness and kurtosis, maximum 2-sigma airborne equipment error, and number of samples for along-track, crosstrack, northing, and easting errors.

The following cases are considered positive errors: LORAN-C determined position further north, farther east, closer to "FROM" waypoint, or further to the right (referenced to direction of travel) than actual aircraft position. It can be shown that the vector summation of north and east errors and the vector summation of along-track and crosstrack errors have the same magnitude. They differ in direction only by the amount by which desired track differs from true north. The same can also be shown for the means and standard deviations of these parameters.

Maximum 2-sigma easting error is the sum of the absolute value of mean easting error plus twice its standard deviation. Maximum 2-sigma northing error is calculated similiarly. The maximum 2-sigma airborne equipment error is the magnitude of the vector summation of

these two errors. It is the maximum error in the direction of worst error for 95 percent of all data samples. (Tables 3, 4, and 8 were calculated this way.)

FTE was computed from TDL-711 horizontal deviation signals. Recorded cross-pointer deflections were converted to nautical miles and means. Standard deviations and 2-sigma maxima were computed. (Table 7 was derived this way.)

Coefficients of skewness and kurtosis are measurements of an error distribution's departure from the ideal Gaussian distribution or bell-shaped curve. Skewness is the amount by which the mean or average differs from the median; that point for which half the samples are above and half below. Kurtosis is a measure of the shape of a distribution of samples. A group of data with more samples than usual near the mean and fewer than usual at moderate differences will show a sharply pointed distribution curve and a kurtosis greater than three. This is called leptokurtic. The opposite is called platykurtic with a coefficient less than three. Most route width and spacing criteria, including AC 90-45, make the assumption that navigation system errors have Gaussian distribution, and skewness and kurtosis become important only if they show a distribution to be non-Gaussian. The LORAN-C error distributions shown in this report are not significantly non-Gaussian; thus, no skewness or kurtosis data are included.

TSCT was computed from aircraft tracking data and desired course. It is the distance the aircraft deviated left or right of its desired track. Mean, standard deviation, and maximum 2-sigma errors were computed for each segment and for the data as a whole (two standard deviation plus). It is an independant measure of total LORAN system performance, including ground facilities, airborne equipment, and pilot/aircraft.

A typical error plot is shown in figure 14. This segment is part of an approach to the Pacesetter III oil platform. The northing and easting error plots show LORAN-C sensed position to be consistently southeast of the helicopter's actual position. The flight was southeast-bound on this leg, so the crosstrack error is nearly zero and the along-track error is negative (i.e., LORAN-C distance-to-waypoint is smaller than actual distance-to-waypoint).

The signal-to-noise ratio plot for this flight is shown in figure 15. The master station shows a signal-to-noise ratio of about 5 dB. The actual signal-to-noise ratio is probably higher than this, but the LORAN receiver does not measure above this value.

From 0956 to 1002 hours the signal-to-noise ratio of the Caribou secondary was so low that the receiver was unable to track. This is shown by the out-of-track indication at the top of this secondary's plot. The sawtooth pattern of the Nantucket and Carolina Beach signal-to-noise ratio plots is due to these stations being secondaries in two different LORAN chains with slightly different group repetition intervals. These secondaries are transmitting two pulse trains through a common transmitter and antenna; one pulse train is suppressed or "blanked" when it overlaps the other.

TEST RESULTS

AIRBORNE EQUIPMENT ERROR.

The Seneca, Nantucket, Carolina Beach triad offers the best signal-to-noise ratios and a favorable station geometry in the offshore New Jersey area. Almost all flights into the Baltimore Canyon oil exploration area utilized this triad. The data in table 3 show that the maximum airborne equipment error for all flights using this triad is

TABLE 3. AIRBORNE EQUIPMENT ERROR, INDIVIDUAL SEGMENT

	Airborne Equipment Error, 2-Sigma Maximum, nmi		
	En Route	Terminal	Approach
AC 90-45A Requirements Along-Track and Crosstrack	1.5	1.1	0.30
LORAN-C Equipment Measured Error, Along-Track and Crosstrack	0.52	0.51	0.52

slightly greater than 1/2 mile. There is no significant difference between north and east error values for different phases of flight (en route, terminal, or approach) or for different flight path directions, so the same data are valid for both crosstrack and along-track cases. Thus, LORAN-C can meet the accuracy requirements of AC 90-45A for en route and termimal operations but not for nonprecision approaches.

These results represent the 95 percent probability level for the individual segment which showed the most severe error during flight testing. The data taken as a whole over the course of this project (table 4) shows similar error values.

TABLE 4. AIRBORNE EQUIPMENT ERROR, TOTAL POPULATION

	Mean	Std. Dev.	2-Sigma Max.	No. of Samples
Northing Error, nmi				
En Route	-0.09	0.05	0.19	28,360
Terminal	-0.09	0.08	0.25	4,923
Approach	-0.09	0.11	0.31	6,440
Easting Error, nmi				
En Route	0.26	0.16	0.58	28,360
Terminal	0.27	0.11	0.49	4,923
Approach	0.26	0.13	0.52	6,440
Airborne Equipment Error, nmi				
En Rroute			0.61	
Terminal			0.55	
Approach			0.61	

The errors are quite consistent through the duration of a flight and across the 3-month span of the project, indicating that there are no short term drift problems. The testing, however, did not extend long enough to detect any annual variations due to snow and ice cover along the northern portions of the signal propagation paths.

TOTAL SYSTEM ERROR.

Total system crosstrack error is presented in table 5. These data show that the LORAN system can meet the specifications of AC 90-45A for all phases of flight with the exception noted below. Total system along-track error is the same as airborne equipment along-track error; these data are presented again in this table.

These figures are the 95 percent probability level errors for the segments on which the most severe errors were encountered. The test program data taken as a whole (table 6) yields slightly lower error values.

TABLE 5. TOTAL SYSTEM ERROR, INDIVIDUAL SEGMENT

	Total System Error, 2-Sigma Max; nmi		
Along-Track	En Route	Terminal	Approach
AC 90-45A reqs.	1.5	1.1	0.3
LORAN System Measured Error	0.52	0.51	0.52
Crosstrack			
AC 90-45A reqs.	2.5	1.5	0.6
LORAN System Measured Error	1.07	0.78	0.55

TABLE 6. TOTAL SYSTEM ERROR, TOTAL POPULATION

	Average Crosstrack Error Values, nmi			
	Mean	Std. Dev.	2-Sigma Max.	No. of Samples
En Route	0.10	0.28	0.66	20,382
Terminal	0.15	0.20	0.55	2,409
Approach	0.12	0.15	0.42	4,407

On several flights the first segment outbound from the Center showed errors of as much as 2.5 nmi crosstrack. The aircraft had lifted off in the direction of the first waypoint and had overflown the waypoint by several miles before turning to intercept the departure track. The pilots are quite busy in the first few minutes after lift-off with air traffic control (ATC) communications, checking engine instruments, trimming the aircraft, etc., and this caused the navigation blunder. This was not seen in any of the departure segments flown offshore following a point-in-space approach to an oil platform. A contributing factor is the closeness of the first departure segment waypoint to the lift-off spot (within 2 miles). These terminal segments were not considered when determining AC 90-45A compliance. Overlays of several approaches and departures at the Center are shown in figures 16 and 17. These show the repeatability of the LORAN-C signal over several flights and the effect of overshooting the first waypoint on departure.

FLIGHT TECHNICAL ERROR.

Flight technical error statistics (table 7) were compiled as a cumulative total for the whole flight test program.

It can be seen that the flight test results for terminal and approach phases of flight, at 0.74 and 0.45 nautical miles, respectively, are within the assumed FTE values of AC 90-45A, 1.0 and 0.5 nautical miles. The 0.47 nautical mile FTE value for en route segments is significantly lower than the AC 90-45A figure and reflects the decreased pilot workload during en route operations. Departure segments showing serious overshoot of the first waypoint are not included in these FTE statistics. Minor overshoots are responsible for the terminal FTE values being higher than approach values.

One approach segment, on March 20, 1979, shows an FTE value substantially higher than the AC 90-45A 0.5 nmi figure. This higher value for 1 segment out of 27 is not considered significant.

DIURNAL EFFECTS.

On several occasions, flights were conducted both during daylight hours and again through twilight to determine any possible diurnal effect. No significant difference was noted between day and evening flights for either signal-to-noise ratio or airborne system error. Typical errors are presented in table 8. Signal-to-noise ratios are shown in figures 18 and 19.

TABLE 7 FLIGHT TECHNICAL ERROR, TOTAL POPULATION

Flight Technical Error, nmi

	Mean	Std. Dev.	2-Sigma Max.	No. of Samples
En Route	-0.028	0.22	0.47	20,382
Terminal	0.042	0.35	0.74	2,916
Approach	-0.014	0.22	0.45	5,415

TABLE 8. DIURNAL ERROR STATISTICS

Date: March 30, 1979

Route: FAA Technical Center to New Era Oil Platform and Return via "OIL" Route

Secondary Stations: Nantucket and Carolina Beach

Segment: Departure, Waypoint Clove to Waypoint Brant

Day	Night	Parameter
		Northing error, nmi
-0.14	-0.09	Mean
0.09	0.08	Std. dev.
		Easting error, nmi
+0.24	+0.23	Mean
0.04	0.05	Std. dev.
0.45	0.41	Maximum 2-sigma error, nmi

Segment: En Route, Waypoint Brant to Waypoint OIL-50

Day	Night	Parameter
		Northing error, nmi
-0.08	-0.10	Mean
0.05	0.04	Std. dev.
		Easting error, nmi
+0.22	+0.22	Mean
0.02	0.02	Std. dev.
0.32	0.32	Maximum 2-sigma error

Segment: Approach, Waypoint OIL-50 to New Era Oil Platform

Day	Night	Parameter
		Northing error, nmi
0.07	-0.01	Mean
0.07	0.09	Std. dev.
		Easting error, nmi
+0.26	+0.30	Mean
0.05	0.06	Std. dev.
0.42	0.46	Maximum 2-sigma error

STATION GEOMETRY.

In most cases tested, LORAN-C station geometry did not have a significant effect on position accuracy. Figure 3 in the LORAN-C Fundamentals section of this report shows the relationships between time measurement errors and position errors. The two LOP's shown for each master slave pair are separated by equal time differences. The direction and relative magnitude of a position error due to a TD error is shown by the distance between pairs of LOP's. For example: figure 3A would seem to indicate that given equal measurement errors for both Seneca-Dana TD and Seneca Nantucket TD, north-south position error should be about twice east-west error. This was not the case. East-west error was found to be slightly larger than north-south error. Signal-to-noise ratios, propagation anomalies, etc., apparently have more of an effect on system accuracy. Only in those geometries, with line-of-position crossing angles less than about 30 degrees, does the actual data reasonably agree with the predicted results. In figure 3D the LOP crossing angles show a much larger predicted east-west error than north-south. The data bears this out. East-west error for this Seneca-Dana Carolina Beach triad is an order of magnitude greater than north-south error.

Box pattern data, which were used for station geometry tests, are summarized in table 9.

TURN PERFORMANCE.

A composite of LORAN position errors during turn maneuvers is presented as figure 20. The data spans a 2-minute interval centered on the apex of the turn. There are five turns presented in overlay: two of 45 degrees, two of approximately 90 degrees, and one greater than 180 degrees. It can be seen that the receiver did not unlock or show any unexpected errors.

DATA ANOMALIES.

Some data taken using the Seneca, Carolina Beach, Caribou triad show consistant east-west errors of approximately 1.25 nmi, other data show errors about 0.4 nmi. This discrepancy is explained by the fact that the receiver did not always track the third cycle of the Caribou secondary station pulse envelope as it should have. It tracked the fourth cycle, thus, showing an error of one cycle or 10 microseconds. This 10-microsecond error is equivalent to a shift of lines-of-position in an east-west direction approximately 2 nmi. The failure of the receiver to

TABLE 9. STATION GEOMETRY STATISTICS

	Mean Northing Error (nmi)	Mean Easting Error (nmi)
Seneca, Carolina Beach, Nantucket	-0.07	+0.34
Seneca, Carolina Beach, Caribou	-0.06	+0.43/+1.26*
Seneca, Dana, Nantucket	0.34	+0.43
Seneca, Dana, Carolina Beach	-0.07	-1.01

* Easting error for the Seneca, Carolina Beach, Caribou triad showed two distinct error values (refer to "Data Anomalies" section). The leg-to-leg consistency of the box pattern data show that airborne equipment errors are independent of the direction flown.

track the proper cycle was most likely due to the poor signal-to-noise ratio of the Caribou signals in the New Jersey area. This discrepancy is seen in some of the box pattern data.

A similar cycle-tracking discrepancy was seen in the offshore flight of March 23, 1979, using the Seneca, Nantucket, Carolina Beach triad. This and several other flights early in the program utilized TDL-711 LORAN components on loan from another project activity. This other system was an early production model and did not incorporate several modifications made to the newer equipment used in the bulk of the testing. The older system showed signal-to-noise ratios about 5 dB worse than were measured during later flights.

CONCLUSIONS

Long range navigation (LORAN)-C was found to be an accurate, reliable navigation system in the offshore New Jersey oil exploration area.

The TDL-711 is similar in operation to other area navigation and inertial navigation system (INS) systems and required no more than a brief period of pilot familiarization. No significant operational problems were encountered other than the proximity of the first waypoint to the departure point. Signal coverage is good in the test area with a strong primary triad, Seneca, Nantucket, Carolina Beach, providing optimum geometry and good signal-to-noise ratios.

Accuracies of 1/2 mile or better are possible, given the proper selection of triads. No diurnal effects were found and station geometry is not a contributing factor to accuracy in most cases. The system can meet the requirements of Advisory Circular (AC) 90-45A for all cases except along-track accuracy on a nonprecision approach. Flight technical error for terminal and approach operations was found to be in agreement with the values assumed in AC 90-45A, and substantially lower for en route segments.

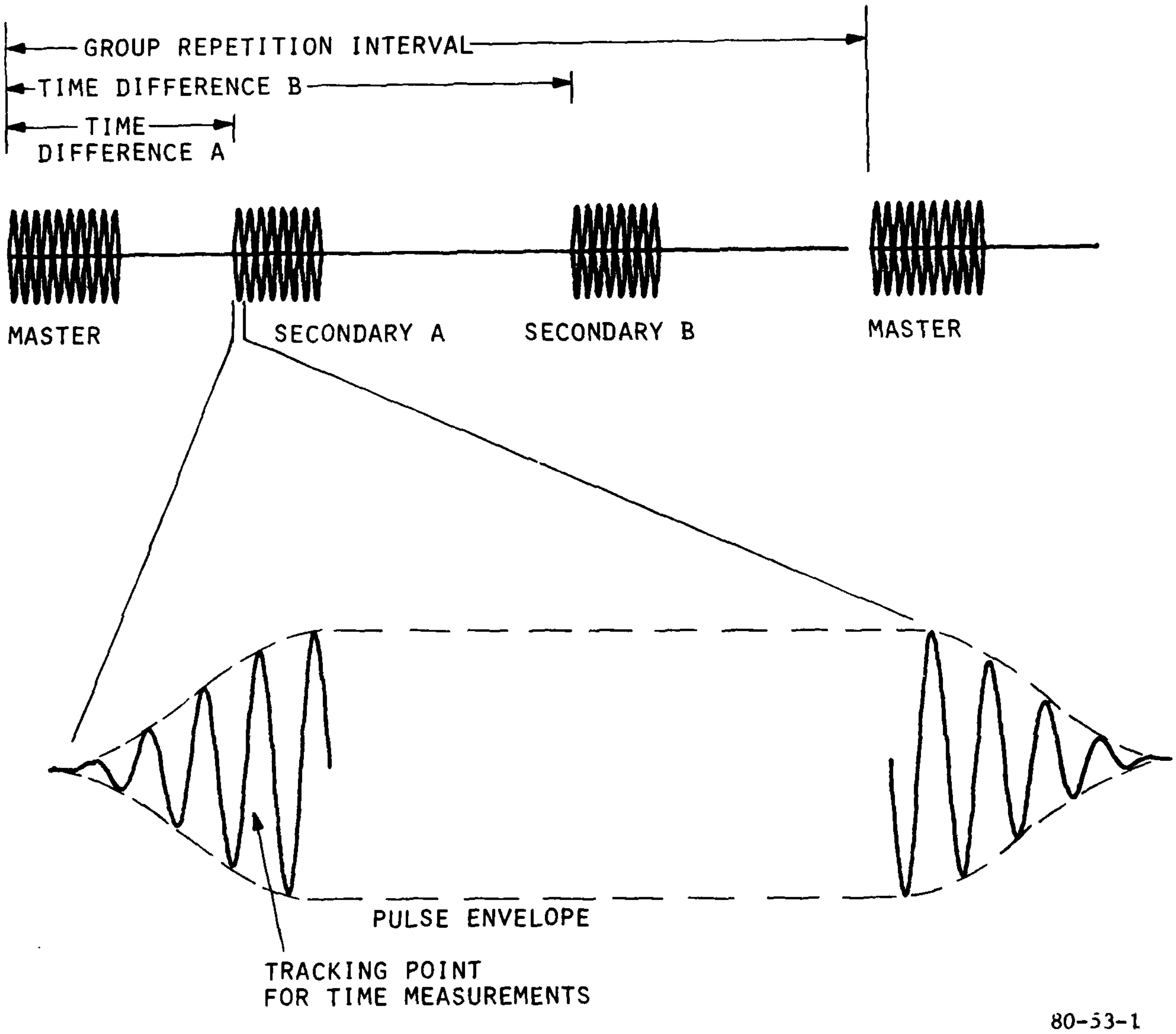
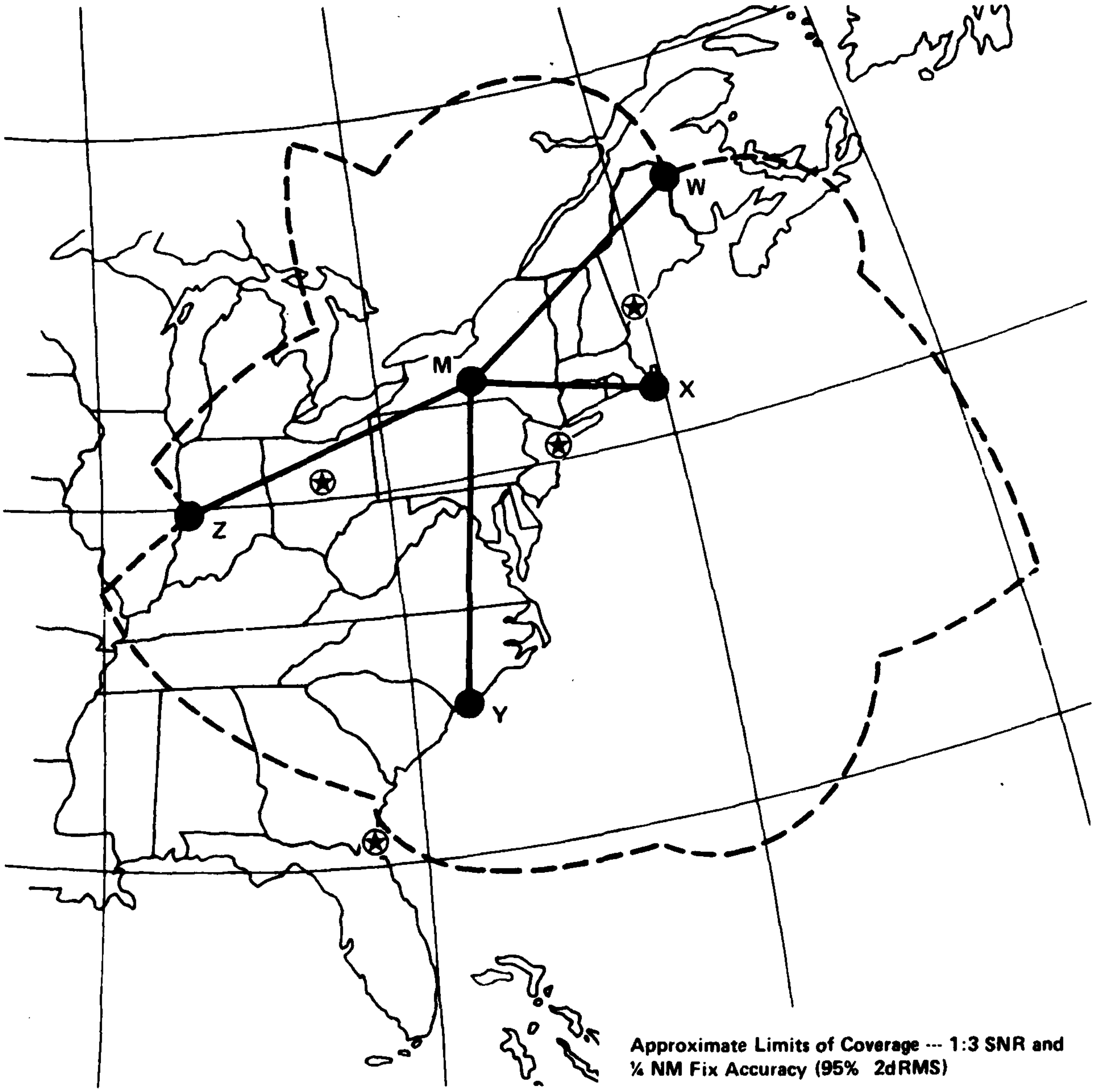


FIGURE 1. LORAN-C PULSE TRAIN

LORAN-C
NORTHEAST U.S. CHAIN
GRI 9960



Approximate Limits of Coverage --- 1:3 SNR and ¼ NM Fix Accuracy (95% 2dRMS)

LEGEND:
- ● TRANSMITTING
- MONITOR
- MONITOR (AUTOMATED)

M SENECA
W CARIBOU
X NANTUCKET
Y CAROLINA BEACH
Z DANA

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FIGURE 2. NEUS CHAIN COVERAGE MAP

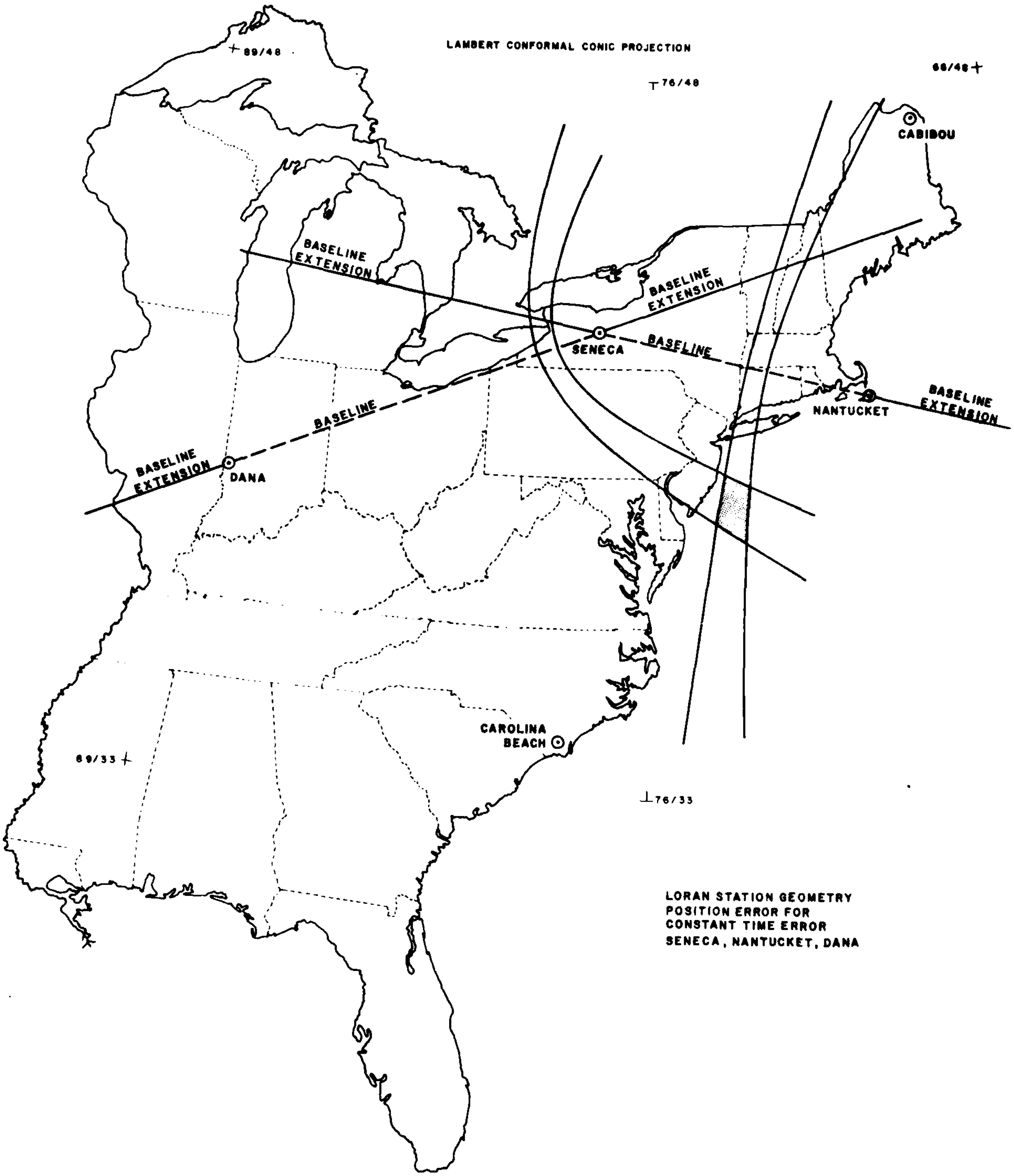


FIGURE 3. LORAN STATION GEOMETRY (Sheet 1 of 4)

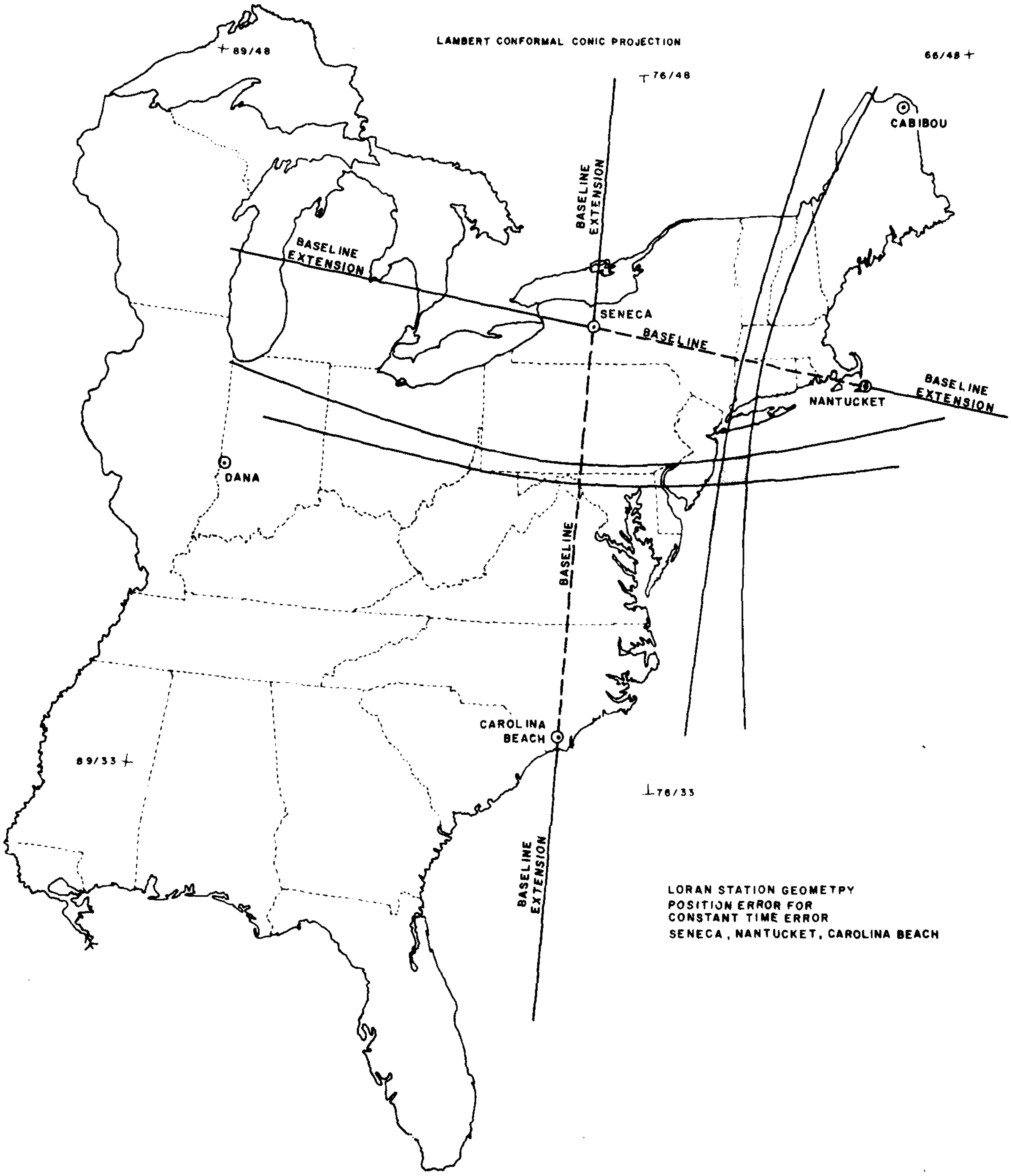


FIGURE 3. LORAN STATION GEOMETRY (Sheet 2 of 4)

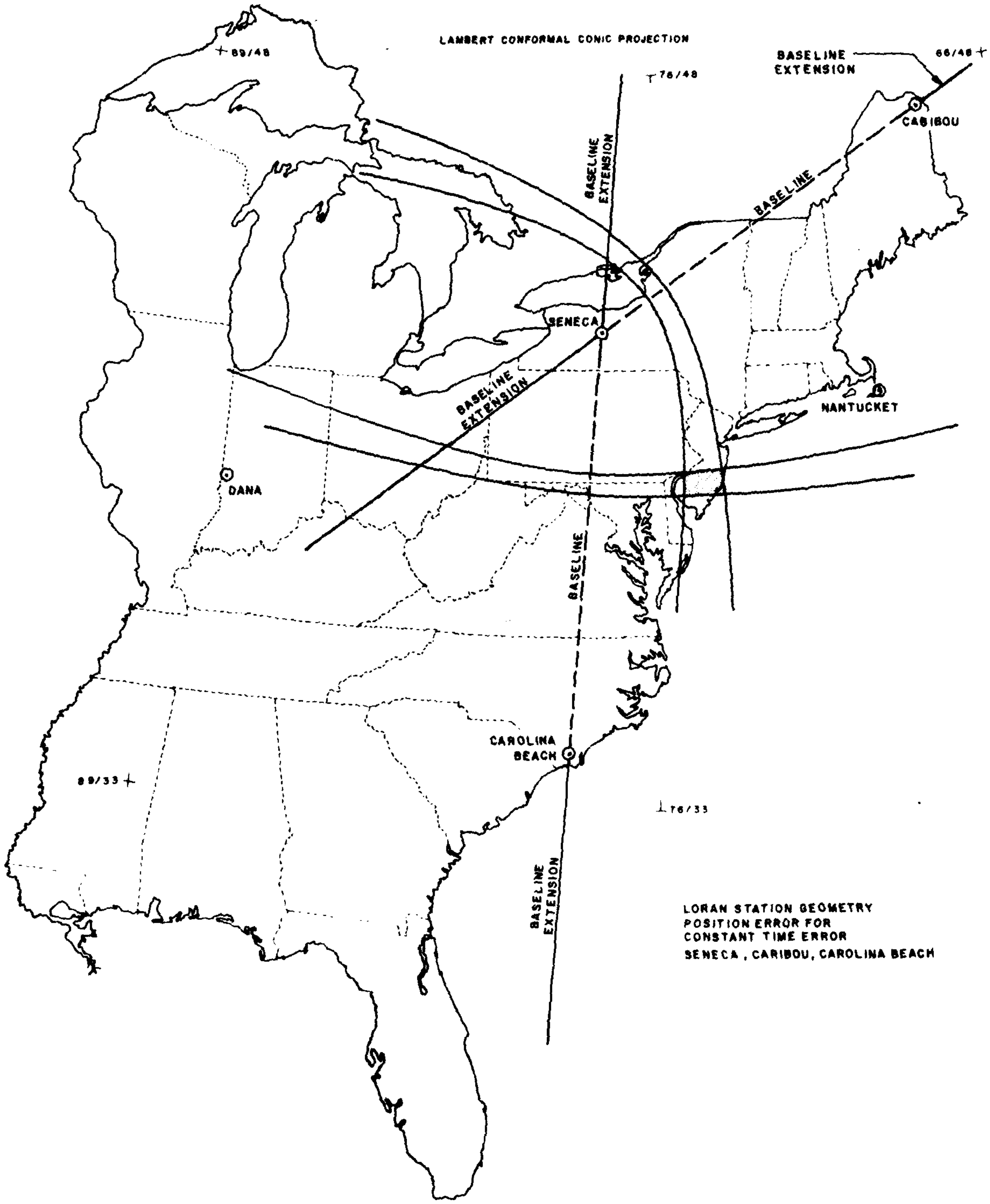


FIGURE 3. LORAN STATION GEOMETRY (Sheet 3 of 4)

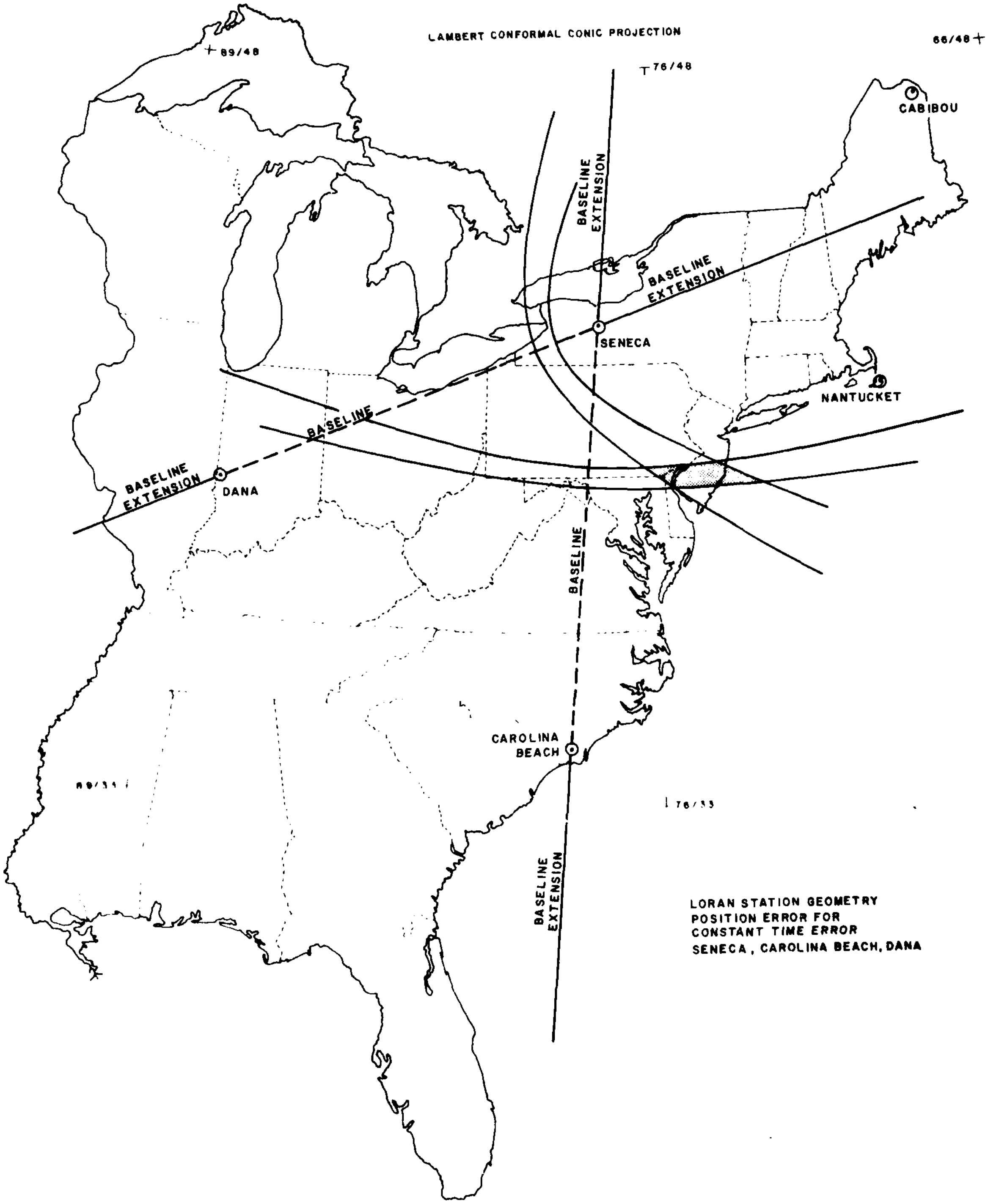
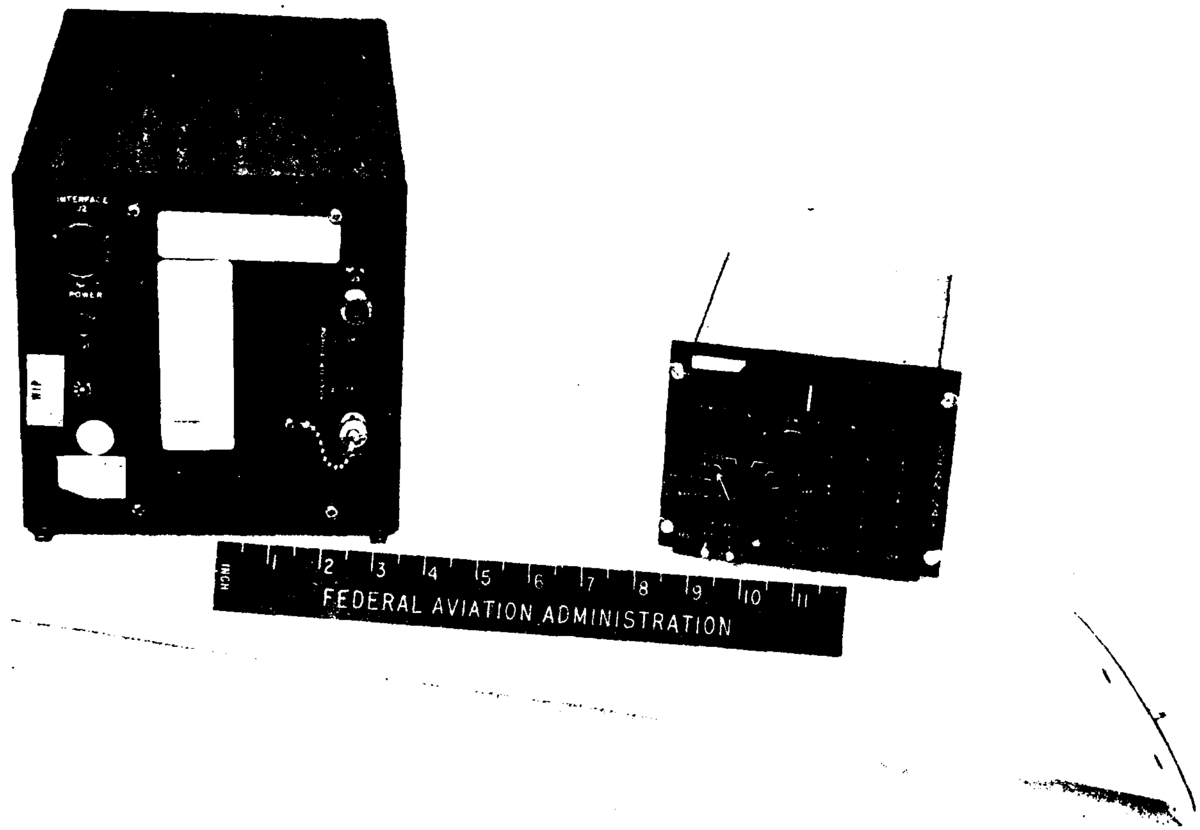


FIGURE 3. LORAN STATION GEOMETRY (Sheet 4 of 4)



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FEDERAL AVIATION ADMINISTRATION

80-0818

FIGURE 4. TDL-711 SYSTEM EQUIPMENT

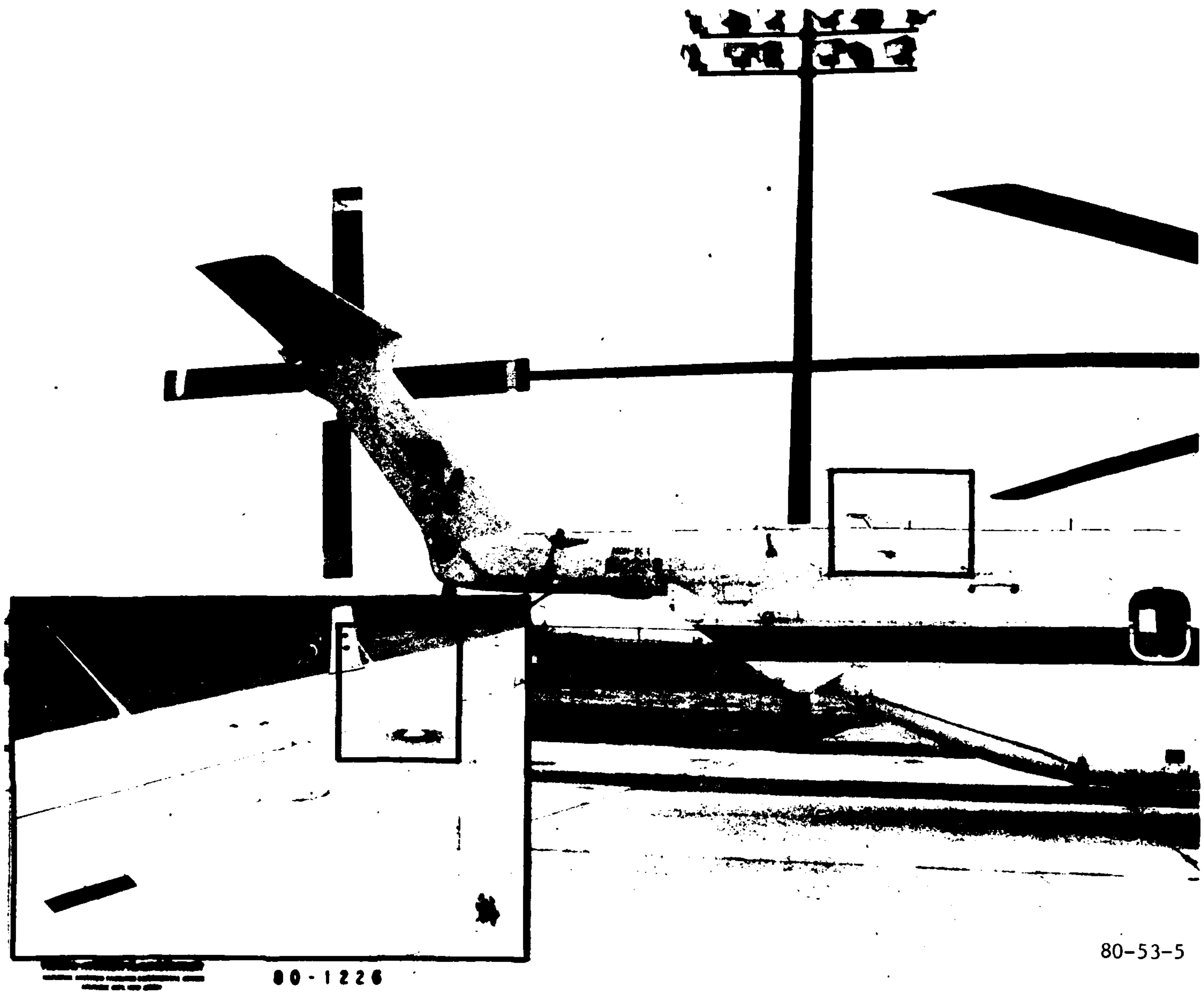

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FIGURE 5. TDL-711 ANTENNA INSTALLATION

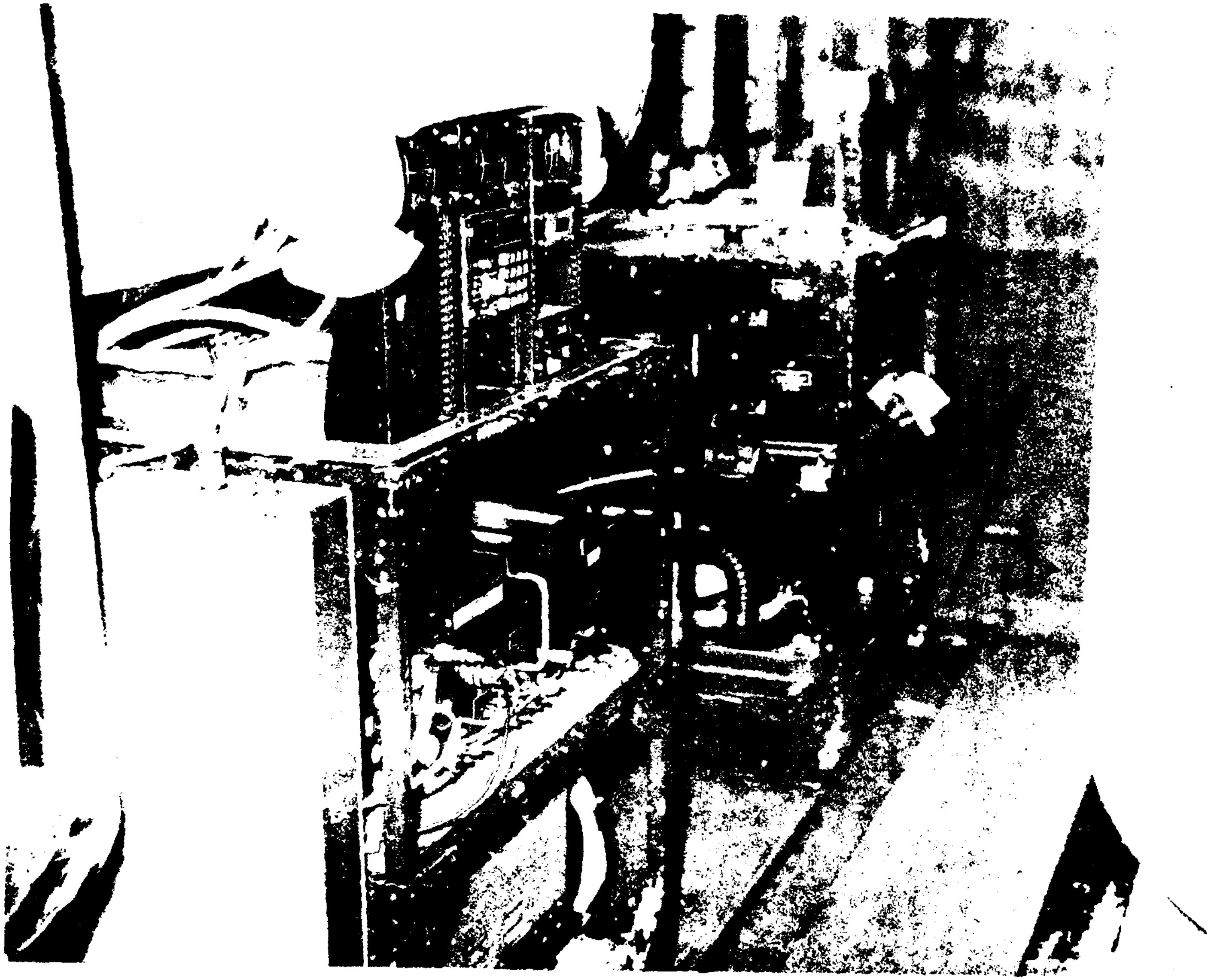

FIGURE 6. TDL-711 RPU INSTALLATION

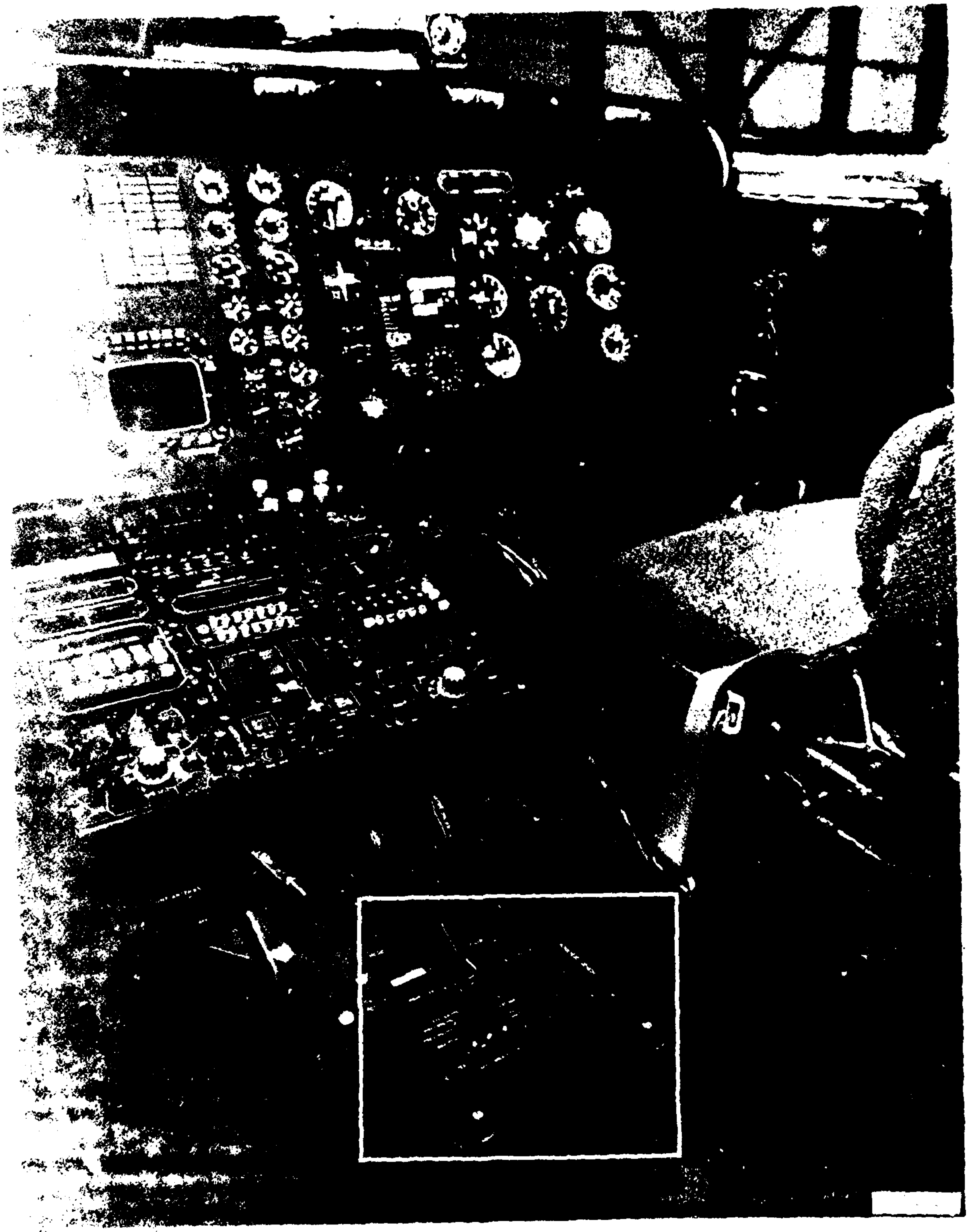

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FIGURE 7. TDL-711 CDU INSTALLATION

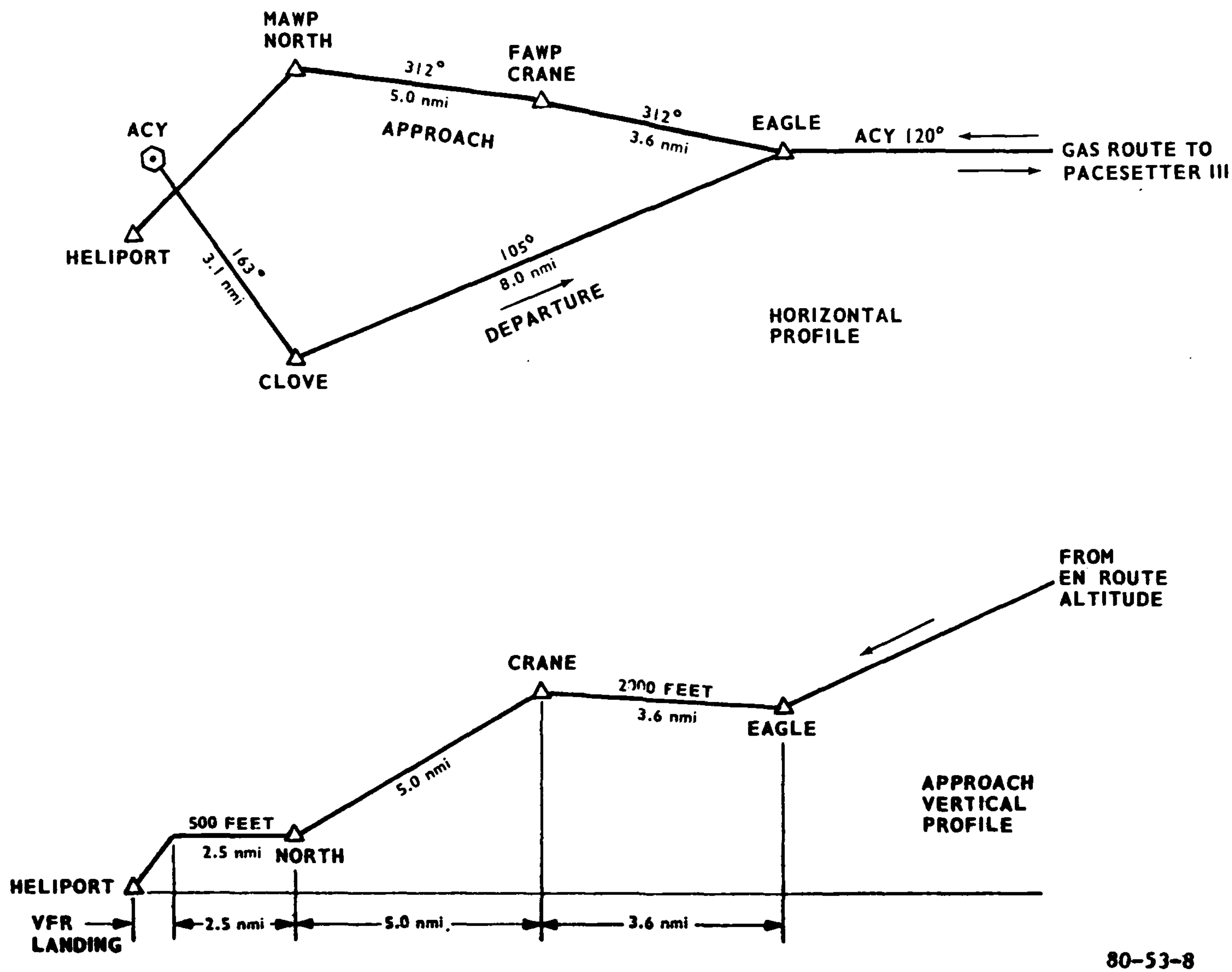

FIGURE 8. GAS ROUTE DEPARTURE AND APPROACH

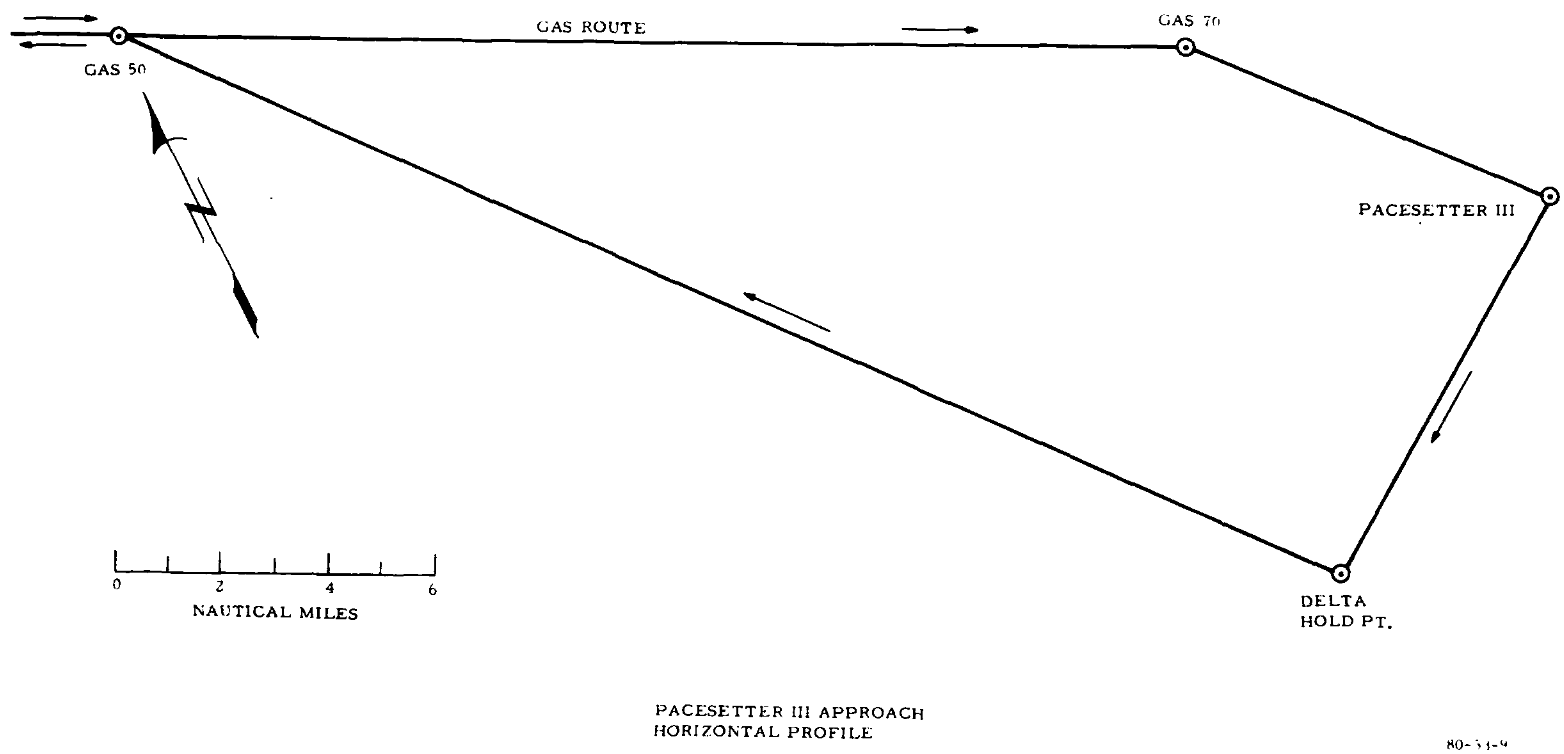

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FIGURE 9. PACESETTER IV APPROACH HORIZONTAL PROFILE

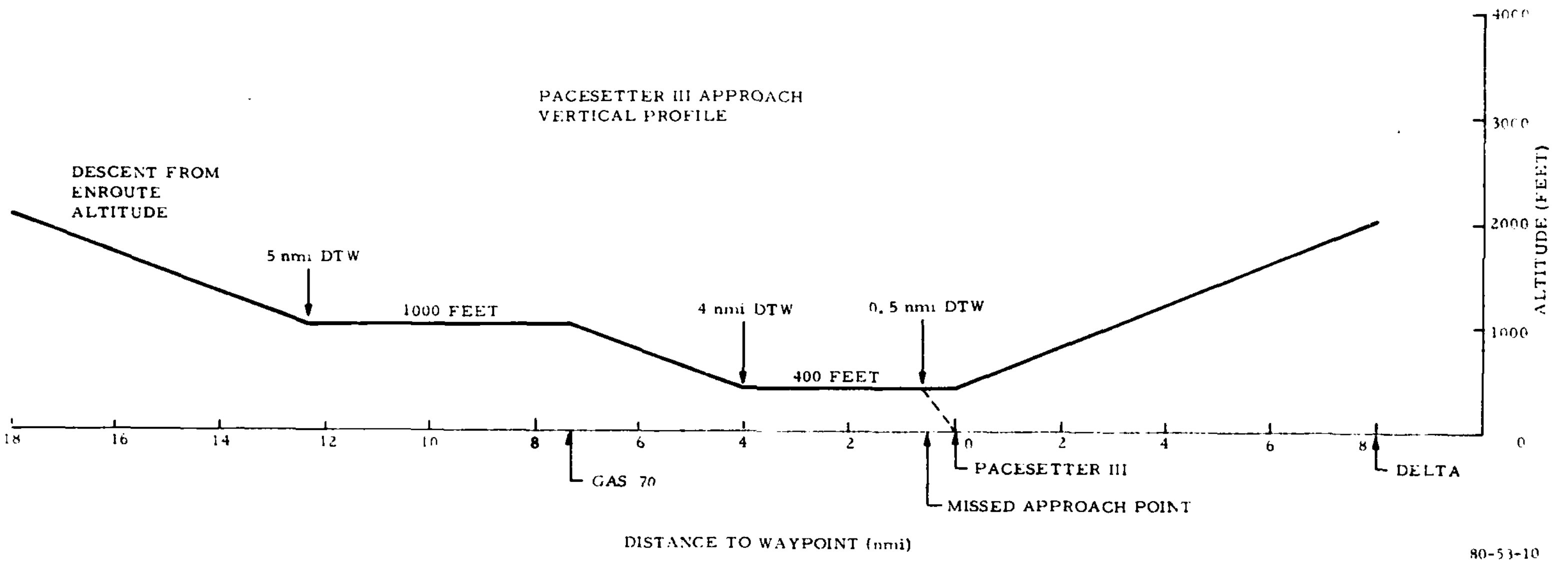

FIGURE 10. PACESETTER IV APPROACH VERTICAL PROFILE

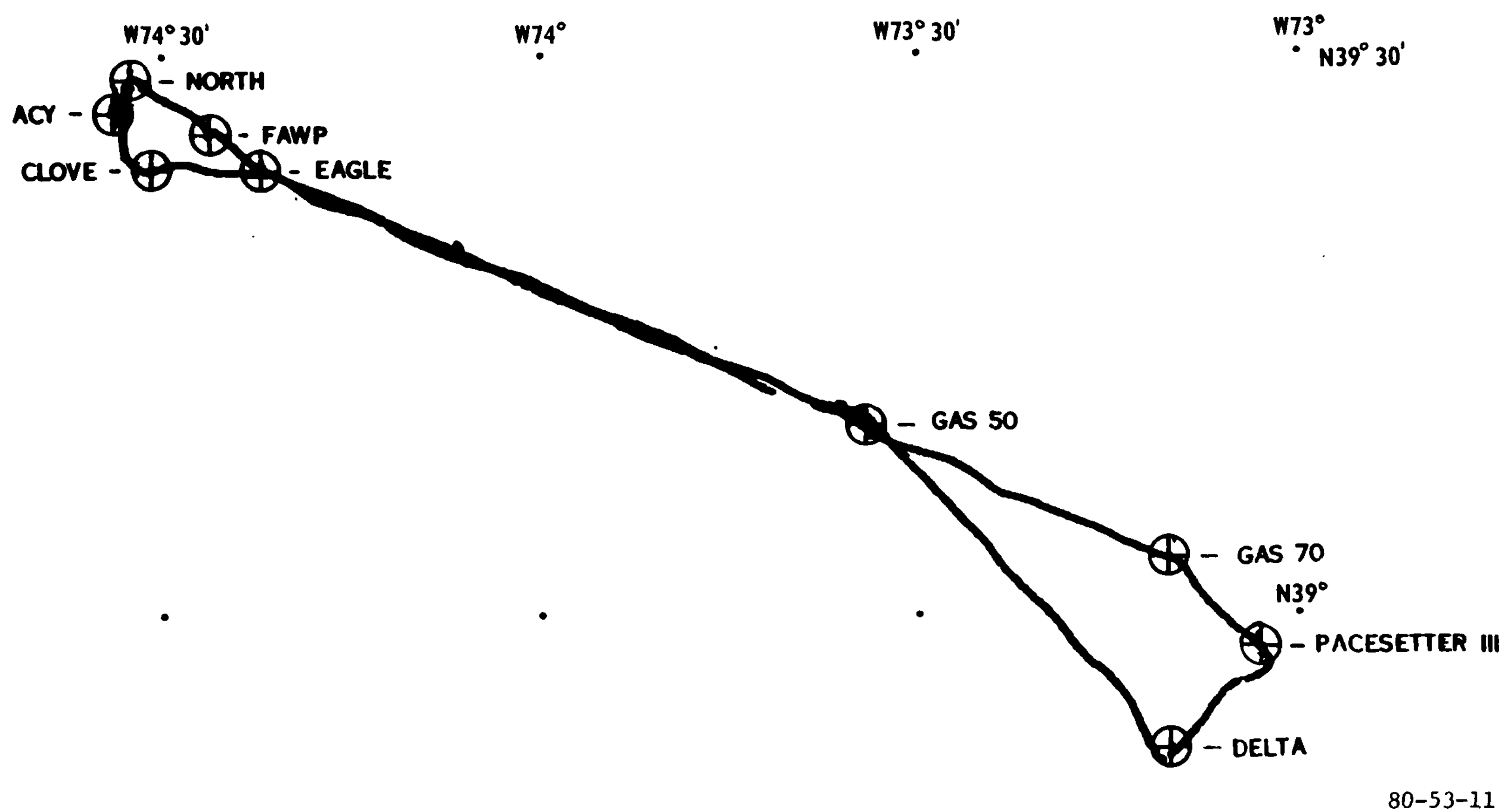

FIGURE 11. PACESETTER IV FLIGHT HORIZONTAL PROFILE

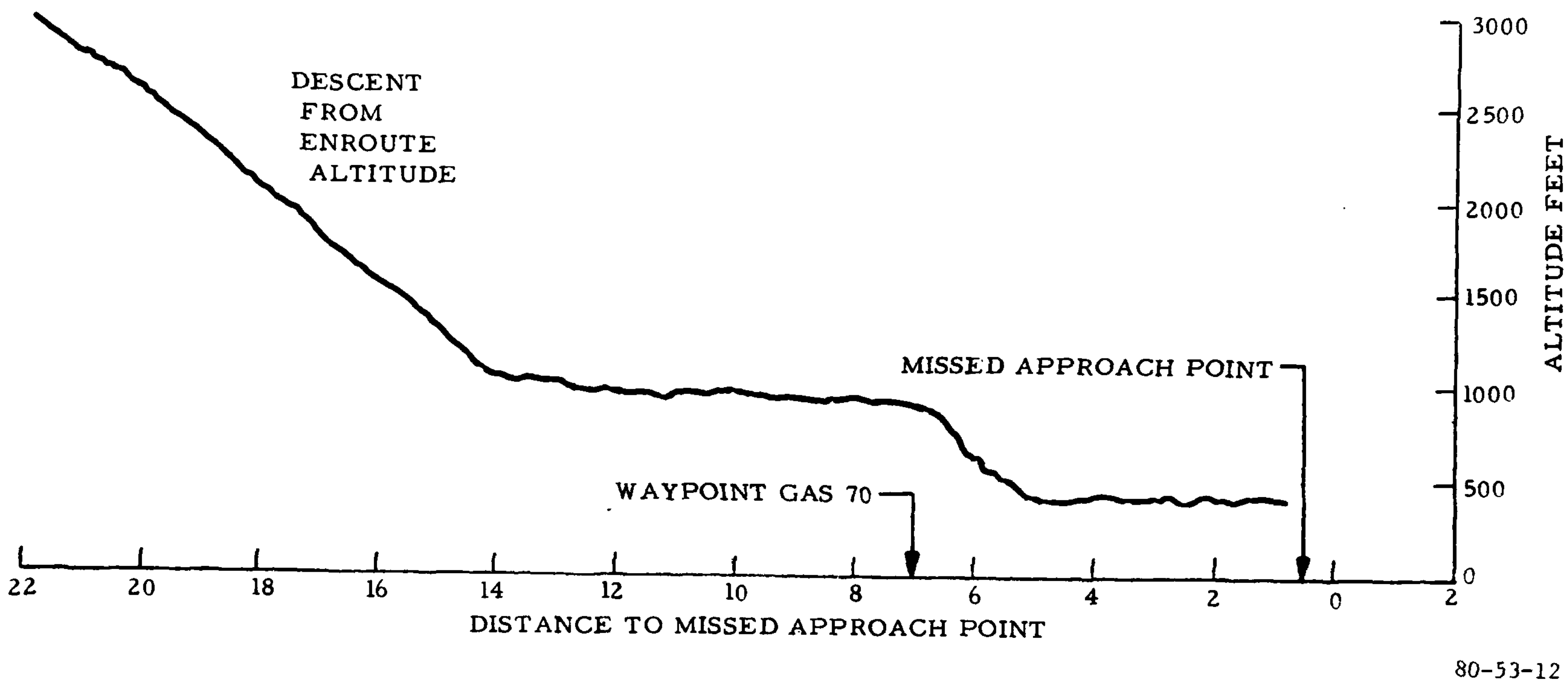

FIGURE 12. PACESETTER IV FLIGHT VERTICAL PROFILE

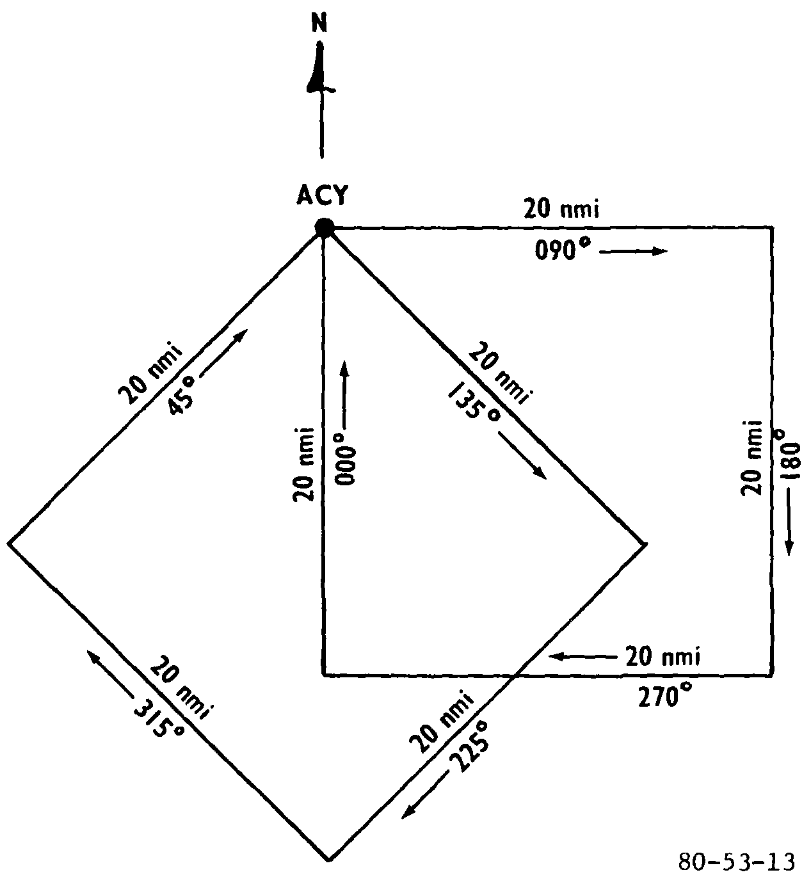

FIGURE 13. DOUBLE BOX PATTERN

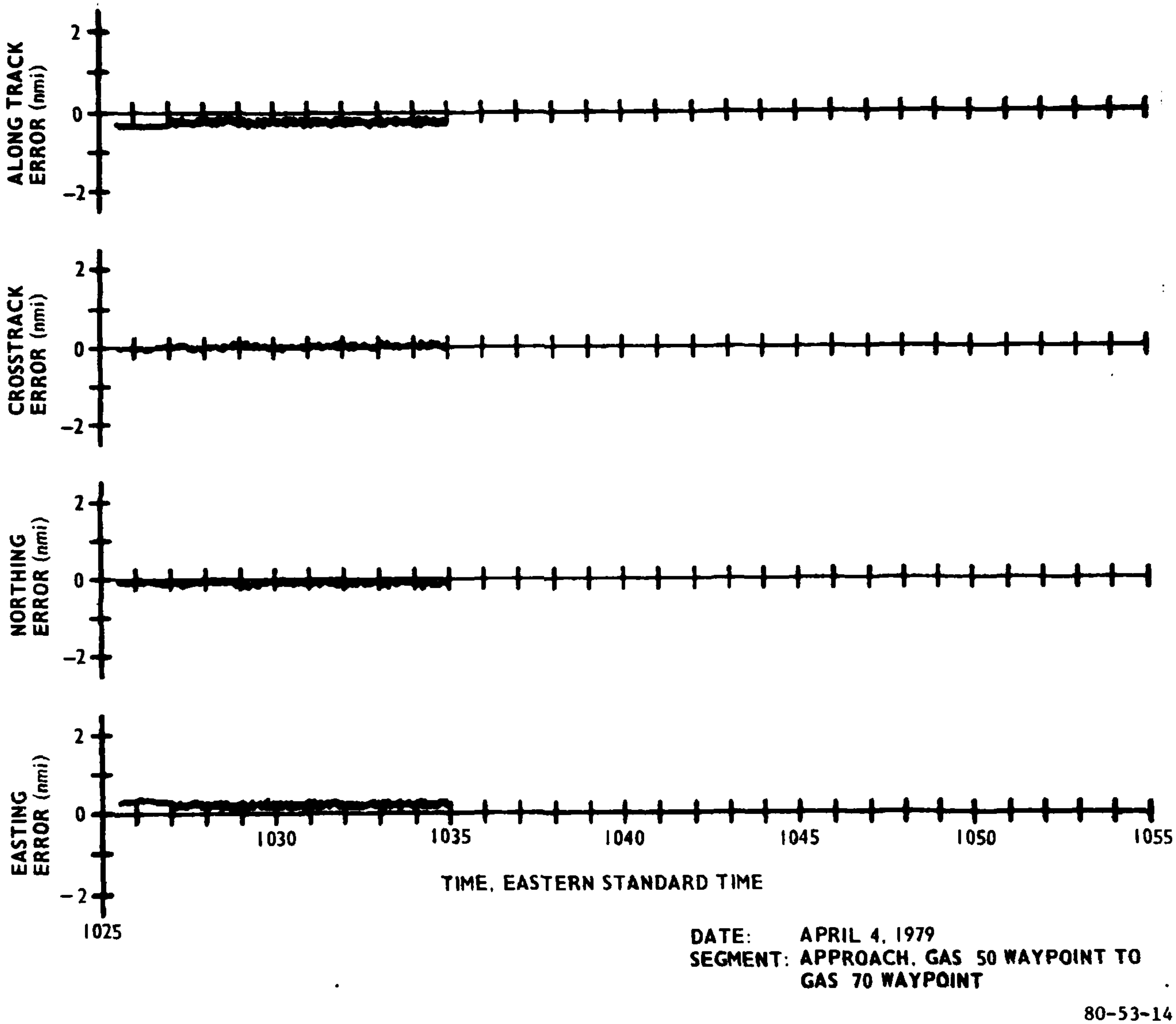

FIGURE 14. TYPICAL ERROR PLOT

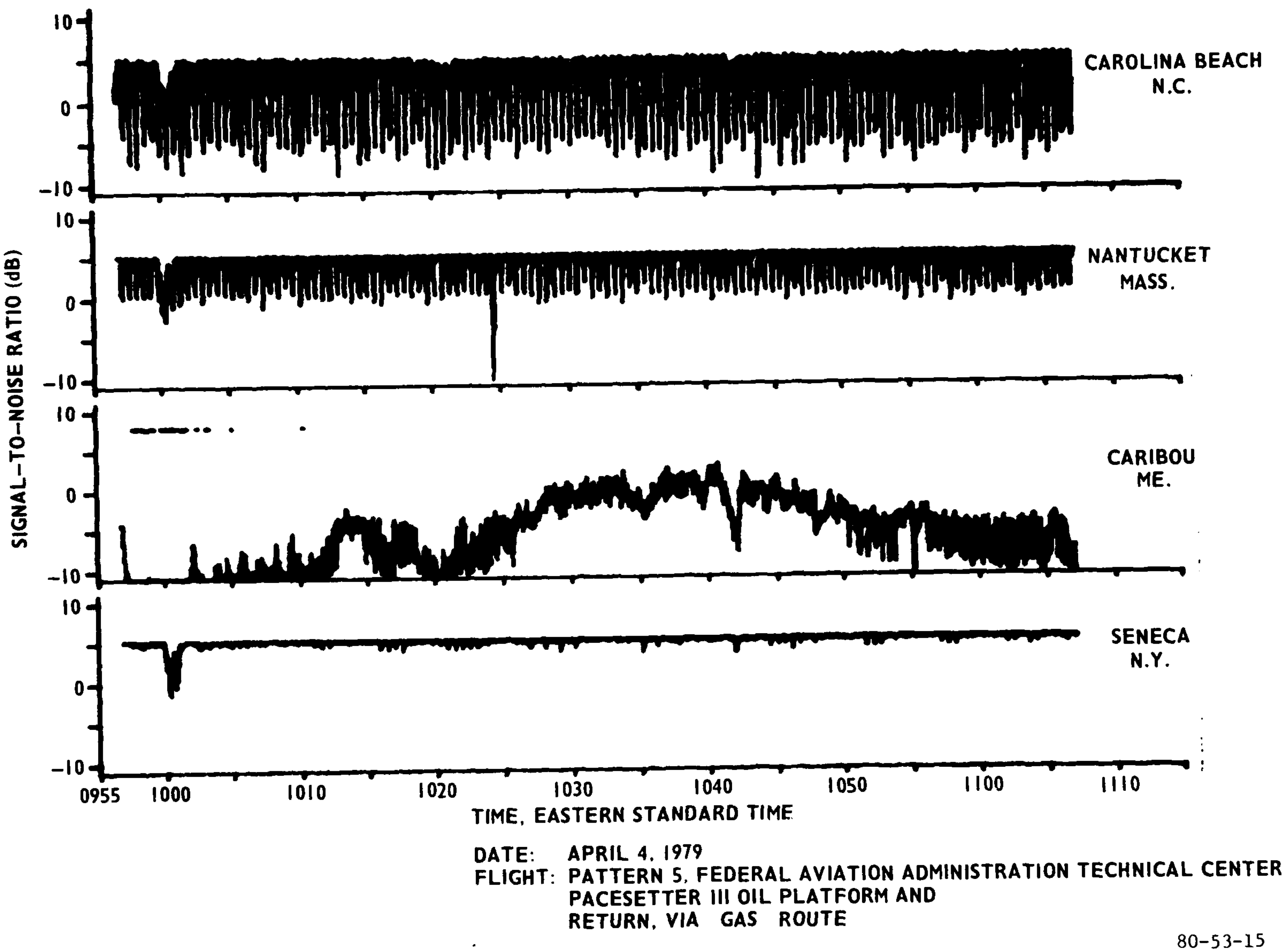

FIGURE 15. TYPICAL SIGNAL-TO-NOISE RATIO PLOT

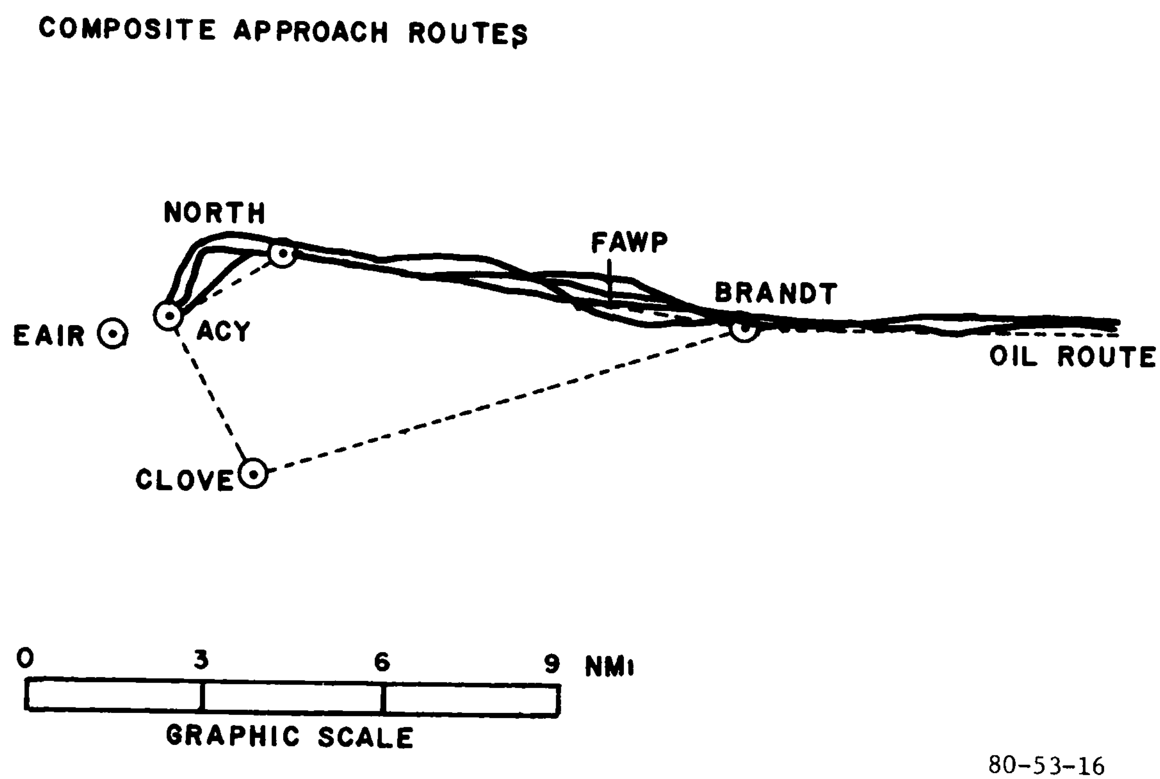

FIGURE 16. COMPOSITE APPROACH FLIGHT PATHS

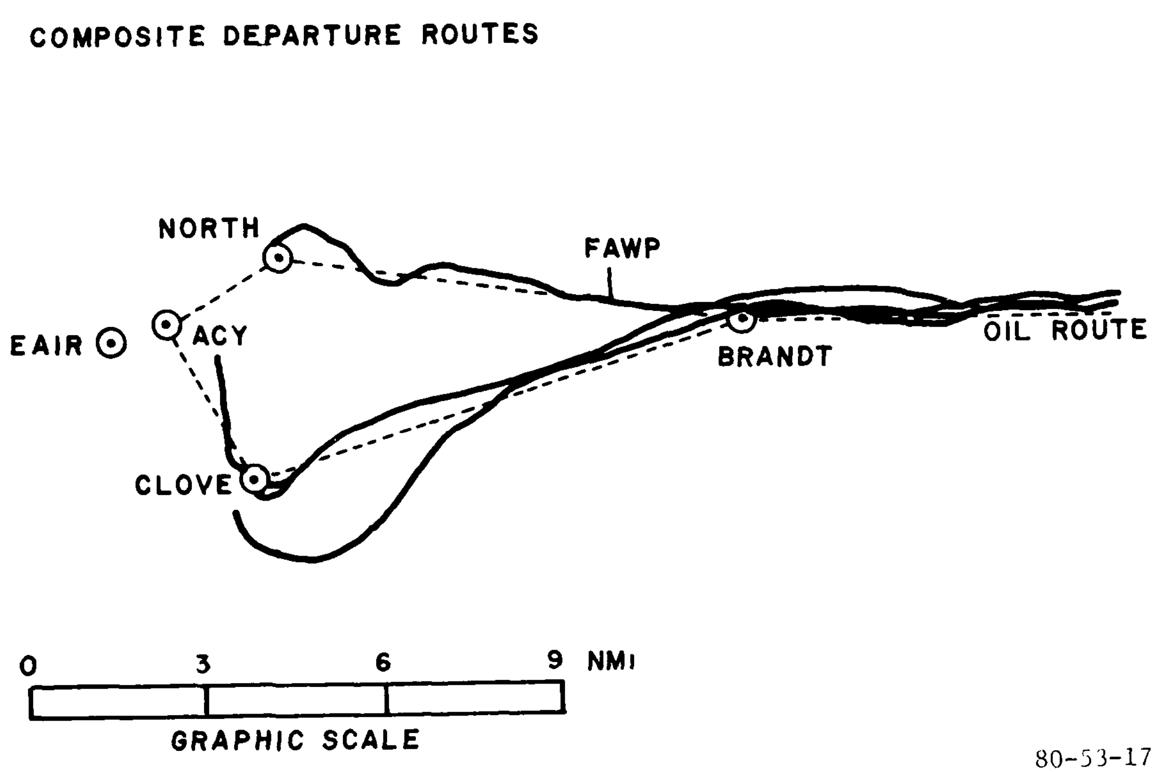

FIGURE 17. COMPOSITE DEPARTURE FLIGHT PATHS

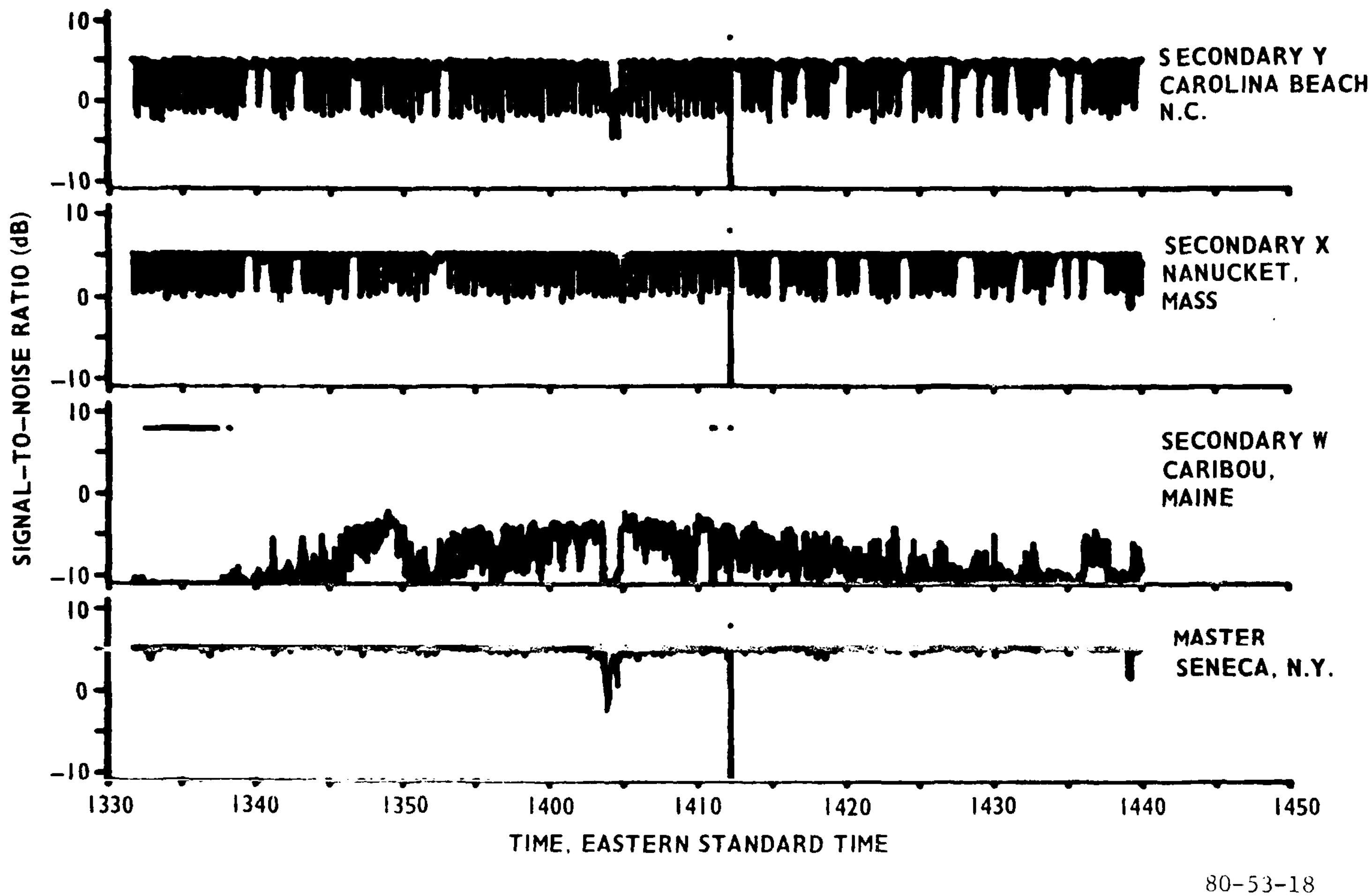

FIGURE 18. DAYLIGHT FLIGHT SIGNAL-TO-NOISE RATIO PLOT

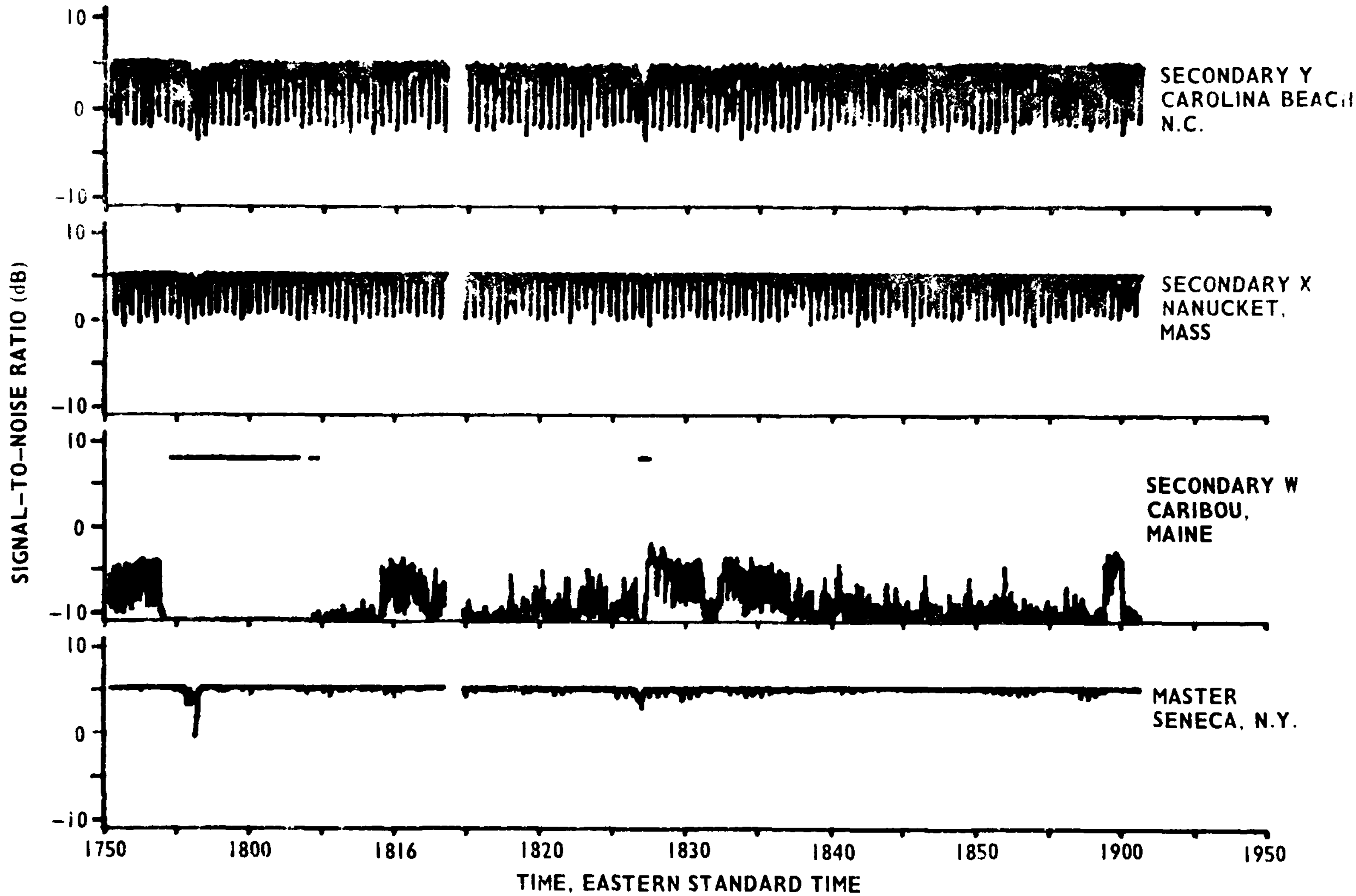

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FIGURE 19. TWILIGHT FLIGHT SIGNAL-TO-NOISE RATIO PLOT

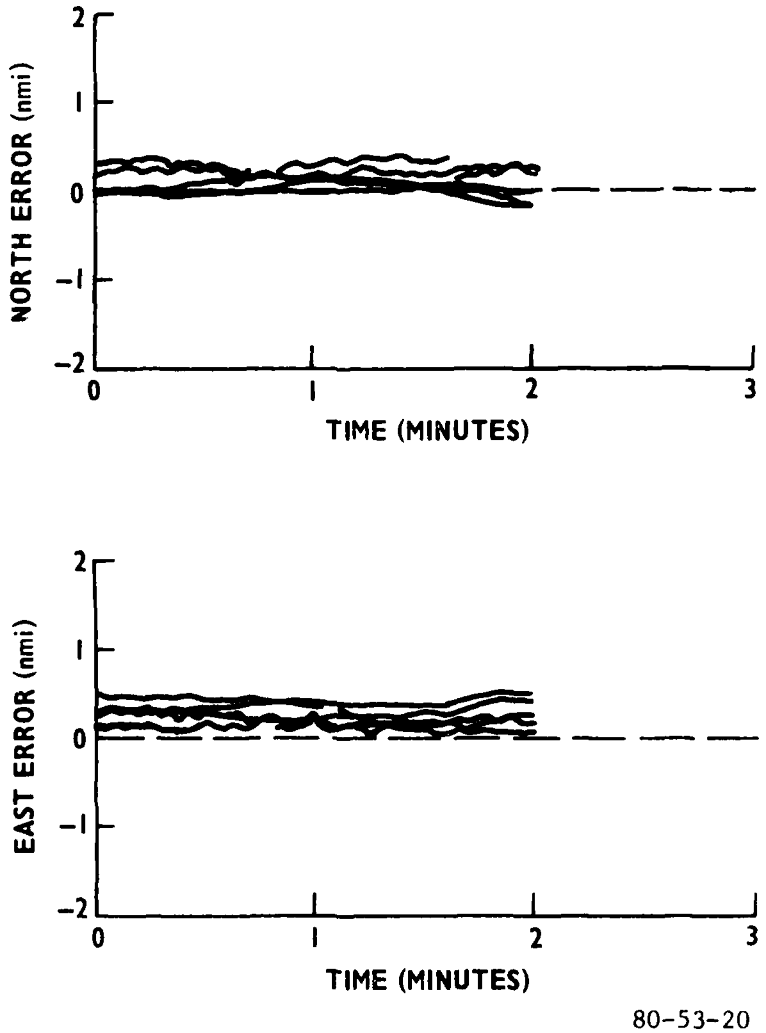

FIGURE 20. TURN MANEUVER ERROR PLOT

APPENDIX A

RECORDED PARAMETERS

GROUND

- Range Time
- Aircraft Latitude, Longitude, Altitude

AIRBORNE

- Range Time
- LTN-51 INS System
    - Latitude
    - Longitude
    - Ground Speed
    - True Heading
    - Ground Track

- TDL-711 LORAN System Nos. 1 and 2
    - Latitude
    - Longitude
    - Time Differences
    - Crosstrack Distance
    - FROM and TO Waypoint Latitude and Longitude
    - Distance to Waypoint
    - Track Status and SNR's, Master and Three Secondaries
    - Envelope Tracking Numbers

- Canadian Marconi CMA-734 Omega System
    - Latitude, Longitude
    - Ground Speed, Ground Track
    - Desired Track
    - Crosstrack Distance
    - TO/FROM

- Aircraft Parameters
    - Pitch, Roll
    - Vertical Speed
    - Barometric Altitude
    - Radar Altitude
    - Flight Director Pitch and Roll Commands

- Communication Components Corporation ONTRAC 3A Omega System
    - Latitude, Longitude
    - Ground Speed
    - Distance To Waypoint